

Planning Combat Outposts to Maximize Population Security

by

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B.S. Psychology
United States Military Academy, 1997

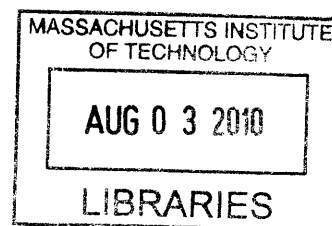
SUBMITTED TO THE SLOAN SCHOOL OF MANAGEMENT IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS OF THE DEGREE OF

MASTER OF SCIENCE IN OPERATIONS RESEARCH

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2010

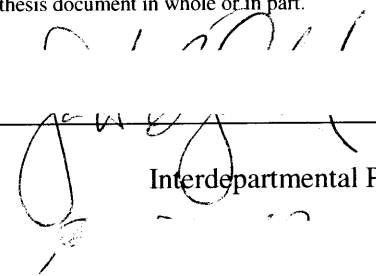


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Report Documentation Page			Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.				
1. REPORT DATE JUN 2010		2. REPORT TYPE		3. DATES COVERED 00-00-2010 to 00-00-2010
4. TITLE AND SUBTITLE Planning Combat Outposts to Maximize Population Security		5a. CONTRACT NUMBER		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, 02139		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited				
13. SUPPLEMENTARY NOTES				
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15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 124
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified		

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Scott B. Seidel

Submitted to the Sloan School of Management on 18 May 2010, in Partial Fulfillment of the
Requirements for the Degree of Master of Science in Operations Research

ABSTRACT

Combat outposts (COPs) are small, well-protected bases from which soldiers reside and conduct operations from. Used extensively during the “Surge” in Iraq, COPs are usually established in populated areas and are prevalent in the counterinsurgency operations in Afghanistan in 2010.

This research models population security to determine combat outpost locations in a battalion area of operation. Population security is measured by level of violence, level of insurgent activity, and effectiveness of host nation security forces. The area of operation is represented as a graphical network of nodes and arcs. Operational inputs include pertinent information about each node. The model allows the commander to set various weights that reflect his understanding of the situation, mission, and local people. Based on trade-offs in patrolling and self-protection, the deterministic model recommends the size and locations for emplacing combat outposts and conducting patrols. We use piecewise linear approximation to solve the problem as a mixed-integer linear program. Results are based on two representative scenarios and show the impact of an area of operation’s characteristics and commander’s weights on COP size and locations.

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Acknowledgments

I would like to thank a number of people that provided guidance and assistance over the past two years.

My deepest gratitude goes out to Richard Hildebrant at Draper Laboratory for his time and patience as my technical advisor. His willingness and enthusiasm to advise me on such a complicated topic as modeling counterinsurgency was remarkable. Many thanks to his red pens and blue highlighters for making me a better writer.

Thank you to Professor Steve Graves at Massachusetts Institute of Technology for his valuable insights advising me on this thesis.

I am grateful to the multitude of Army officers that I conversed with and surveyed to focus my thesis. I would especially like to thank BG H.R. McMaster, COL J.B. Burton, and COL David Barclay.

Thank you to Steve Kolitz, David Carter, and others at Draper Laboratory that assisted me along the way.

My gratitude goes out to the United States Military Academy Department of Mathematical Sciences for the opportunity to complete my masters and to the General Omar N. Bradley Foundation for the research fellowship to pursue this work.

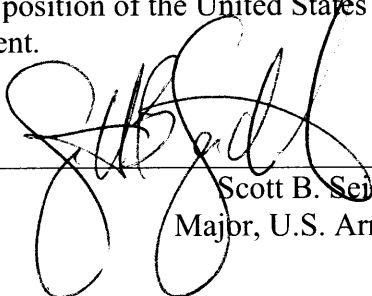
I would be remiss if I did not thank the "Air Force Kids" for without them, I probably would not have passed a class at MIT, nor had as much fun as I did. Back-to-back MIT intramural flag football champions!

As always, thank you to my parents for their continual love and support.

Finally, I dedicate this work to my fallen brethren of Ironhawk: 1LT Justin Smith, SFC Christopher Phelps, SSG Brian Freeman, SPC Robert Pope II, SPC Jared Kubasak, and PFC Mario Reyes. Your sacrifice is never forgotten.

This thesis was prepared at the Charles Stark Draper Laboratory, Inc. Publication of this thesis does not constitute approval by Draper of the findings herein. It is published for the exchange and stimulation of ideas.

As an active duty Army officer, I affirm that the views, analyses, and conclusions expressed in this document are mine and do not reflect the official policy or position of the United States Army, the Department of Defense, or the United States Government.



Scott B. Seidel
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1 INTRODUCTION

1.1 Research Motivation and Description

During my two years as a US Army captain deployed in Iraq, we constantly asked ourselves, “Are we making a difference? What can we do better?” We struggled to define what success was and how to achieve it in a counterinsurgency. As we learned from our experiences in combat, we found our most important focus was securing the populace from violent activities of the insurgents. From these experiences, I wanted to conduct research that could, in some way, assist the decision makers on the battlefield.

This thesis does not attempt to answer the daunting question, “How to win a counterinsurgency?”, nor does it debate the social science theories. Instead, it concentrates on one key prerequisite necessary in attaining the goals of counterinsurgency: security, more specifically, population security. We focus on a key problem faced by military commanders in both Iraq and Afghanistan, “Where do I place my troops to best secure the populace?” The questions where to place outposts and how many soldiers to place at each one is very difficult, but can be one of the most important decisions made.

This research can assist the combat battalion commander and his staff when relieving another unit that conducted initial operations or invasion. It can also assist the realignment of battle space as additional forces enter into a mature theater. Furthermore, the research could aid military planners in determining unit size for areas of operation.

A combat outpost (COP) is a well-defended, permanent base that accommodates a small group of soldiers (anywhere from a dozen to a few hundred soldiers). Commanders must weigh many factors in deciding where to place his COPs. He must appreciate the current situation and also anticipate the future needs of the area. The decision of where to locate COPs depends on what areas are deemed critical to population security and require patrolling. The commander also has to consider the number of troops required to defend the COPs. In general, more COPs require more troops to guard them, which reduce the available soldiers for missions and patrols. As a unit becomes more dispersed, it also becomes more vulnerable to attack. Furthermore, legal obligations with the local government may constrain the locations a commander can place his troops.

Constructing an outpost, or moving one, is very resource intensive and can take several weeks to accomplish. Placing outposts intelligently at the beginning is critical to ensure that future units do not expend energy and resources relocating their outposts. With a limited number of troops and the success of his mission depending on smart allocation, choosing where to build outposts is a critical question.

1.2 Example Scenario

Below is an example scenario to illustrate the challenges this research addresses. You are an infantry battalion commander who is about to conduct counterinsurgency operations in an area resembling New Mexico. You are given the mission to secure and stabilize an area that has recently been ravaged by a civil war. The situation is best described as an insurgency with a significant criminal element. You will assume responsibility of the area of operation that measures approximately 100 km across by 80 kilometers (Figure 1-1). Prior to your arrival, a company of US forces (about 100 soldiers) has been conducting limited operations for the past two months. They pass on general knowledge of the population, recent violence, and attacks on US forces. The departing unit has met with local leaders and has begun working with the local police. They have also collected intelligence on where insurgents have been active. As the commander, you will make hundreds of decisions in the first month alone. One important decision is where to emplace your forces. Do you position them all in a single location, e.g., Roswell, and patrol out from there? Do you situate the soldiers in multiple locations, e.g., some in each major town? How many soldiers do you put at each location?

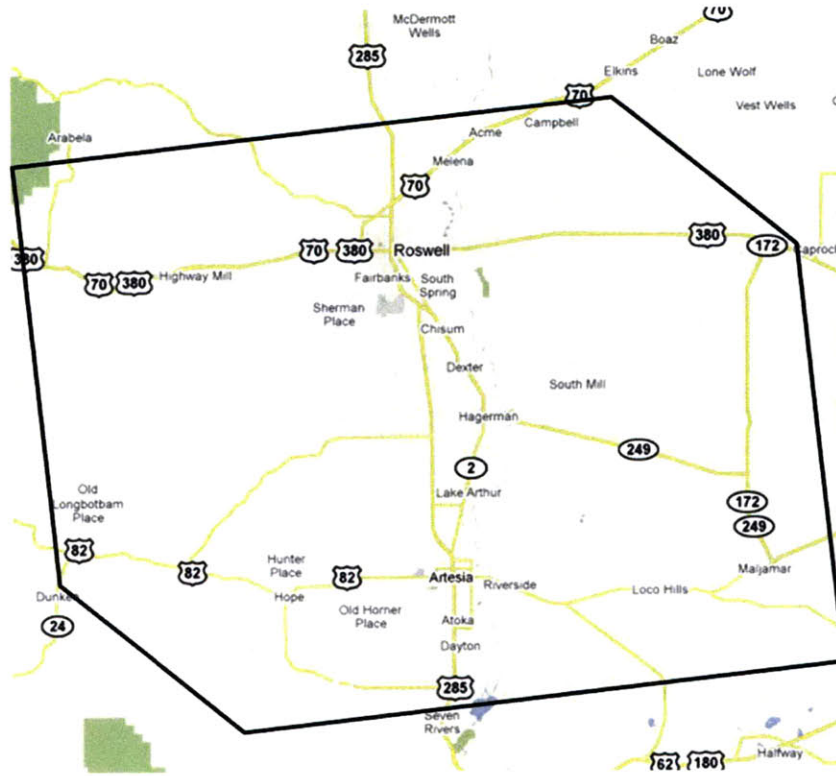


Figure 1-1: Example Battalion Area of Operation

1.3 Facility Location Problems

To create a model for outpost emplacement, we looked at an area of study to provide a foundation for our initial efforts. Facility location problems are a discipline of operations research which attempt to find an ideal location(s) to meet a specified objective. The decision on selecting a location depends on the criteria and constraints [1].

A simple facility location problem might emplace a single facility, with the optimization criterion being to minimize the sum of distances from a given set of sites. In city planning, this decision might be where to build a fire station to provide the best service for all houses in a neighborhood. More complex problems include the placement of multiple facilities, constraints on the locations of facilities, and more complex optimization criteria. Generally, for the facility location problem, we assume that we can specify a set of potential sites where a facility can be opened and a set of demand points that must be serviced. The goal is to pick a subset of these candidate facilities to open which minimizes the total distance (or operating cost) to service the customers from the nearest facilities. In manufacturing or retail, a facility location problem may decide where to establish distribution centers to minimize overall costs for shipping products to

all stores. Solution techniques for facility location problems involve introducing a binary variable to represent the presence or absence of a facility at each potential location. This binary variable is used in constraints to prevent resources from being allocated to locations that do not receive a facility.

The emplacing of soldiers in outposts is similar to a facility location problem. Like a complex facility problem, there are numerous options for COP locations. Among other restrictions, we are constrained by the number of soldiers in the unit. The greatest difference is that of the objective function; instead of minimizing distance or cost, we are maximizing population security.

1.4 Overview

This thesis consists of 5 follow-on chapters. Chapter 2 provides background on the problem. We introduce the relevant background on counterinsurgency topics, as well as specific information on population security and combat outposts. Chapter 3 discusses the model and formulation that addresses the COP location problem. We detail the variables, parameters, and constraints, along with the objective function that models population security based on reduction of violence, reduction of insurgent activity, and improvement of host nation force effectiveness. We approximate the objective function with a piece-wise linear function and are then able to solve the COP location problem as a mixed-integer linear program. Chapter 4 provides results and analysis of the model. We base the research on two representative scenarios and examine how the objective function behaves. We also conduct experiments to evaluate operational considerations on the scenarios. Chapter 5 examines the future research that could enhance and improve the model. Chapter 6 provides some concluding thoughts on the research and the results.

2 BACKGROUND

The goal of this chapter is to provide the underlying aspects of the problem. Because this thesis explores decisions made at the battalion level, we first describe a battalion and its position within the Army. Furthermore, we briefly explain insurgency and how security relates to the successful execution of a counterinsurgency. We chronicle recent events in Iraq that illustrate the challenges of providing security for the population during an insurgency. Finally, we describe combat outposts (COPs) and their usefulness in establishing security for the population.

2.1 The Army

2.1.1 Levels of War

Figure 2-1 summarizes the levels of war, the connection between them, and provides examples of each from the Gulf War in 1991 [2].

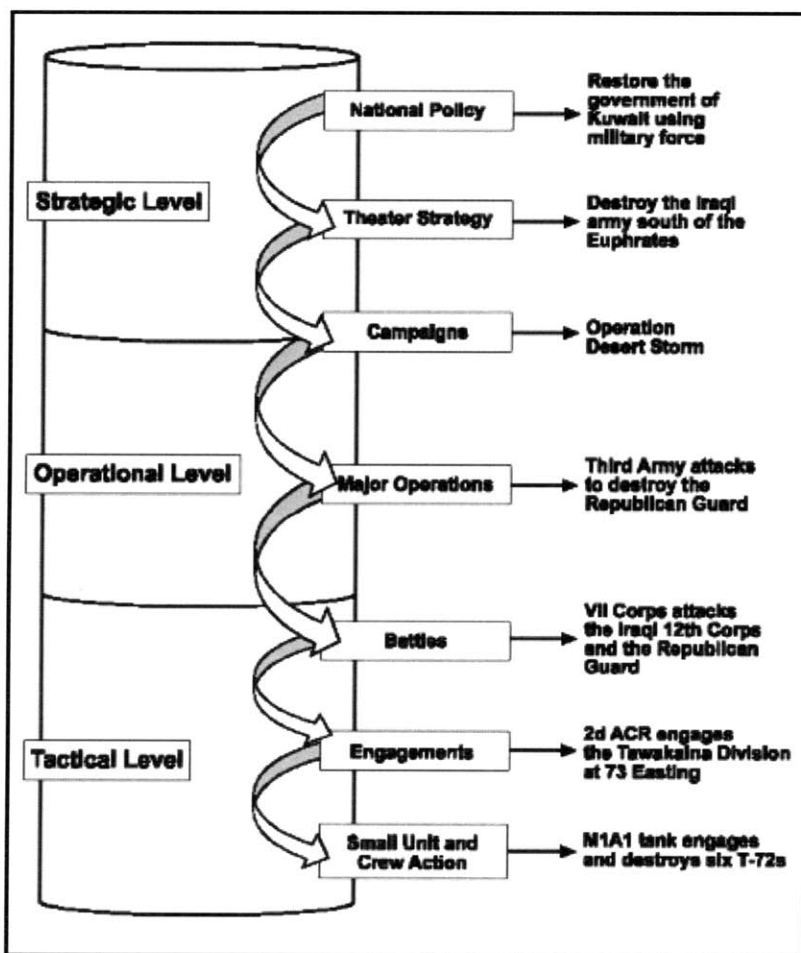


Figure 2-1: Levels of War

The strategic level of war sets the policies and objectives for any conflict that the nation enters. The operational level conducts campaigns by positioning forces to achieve the strategic end state. The tactical level is where individual battles are fought that ensure the success of operations [2].

The tactical level of war usually starts at the division (each contains approximately 20,000 soldiers). Previously, the division was considered the lowest organized unit considered for deploying and sustaining itself. In 2003, the Army began a transformation to a modular system of deployable brigade combat teams (BCTs). The brigade, a unit echelon one lower than division, consists of about 4,000 soldiers. All Army brigade combat teams are standardized into one of three types: heavy, Stryker, or infantry. A heavy brigade combat team (HBCT) contains tracked vehicles: tanks, infantry fighting vehicles, and howitzers. The Stryker brigade combat team (SBCT) is an armored wheeled unit, while the infantry brigade combat team (IBCT) has limited vehicles and is designed around soldiers on foot.

2.1.2 Battalion

The battalion, or squadron, is a subordinate unit of the brigade (each BCT is assigned six battalions/squadrons) and is the lowest level of command that includes a staff for the commander. This staff has the capability to simultaneously plan, prepare, and execute missions, although at a limited capacity. The staff advises and assists the commander on various functions of his unit, to include logistics, operations, and intelligence.

2.1.2.1 Battalion Composition

Two types of battalions are used in this study: the combined arms battalion and the infantry battalion. Both the combined arms battalion and infantry battalion have five organic companies: four combat companies and one headquarters and headquarters company (HHC). During training or combat operations, battalions can be augmented with additional forces such as another company. A combat battalion has between 600 and 700 soldiers (combined arms battalion – 623; infantry battalion – 689).

The combined arms battalion is part of an HBCT and is equipped with tanks and armored personnel carriers, along with a mix of tracked and wheeled vehicles to support operations. The maneuver units of the combined arms battalion are two tank companies, two mechanized infantry companies, and a scout platoon and a mortar platoon in the HHC. A majority of the soldiers in

the HHC are staff or support personnel. Figure 2-2 shows the composition of a heavy brigade combat team and decomposes a combined arms battalion.

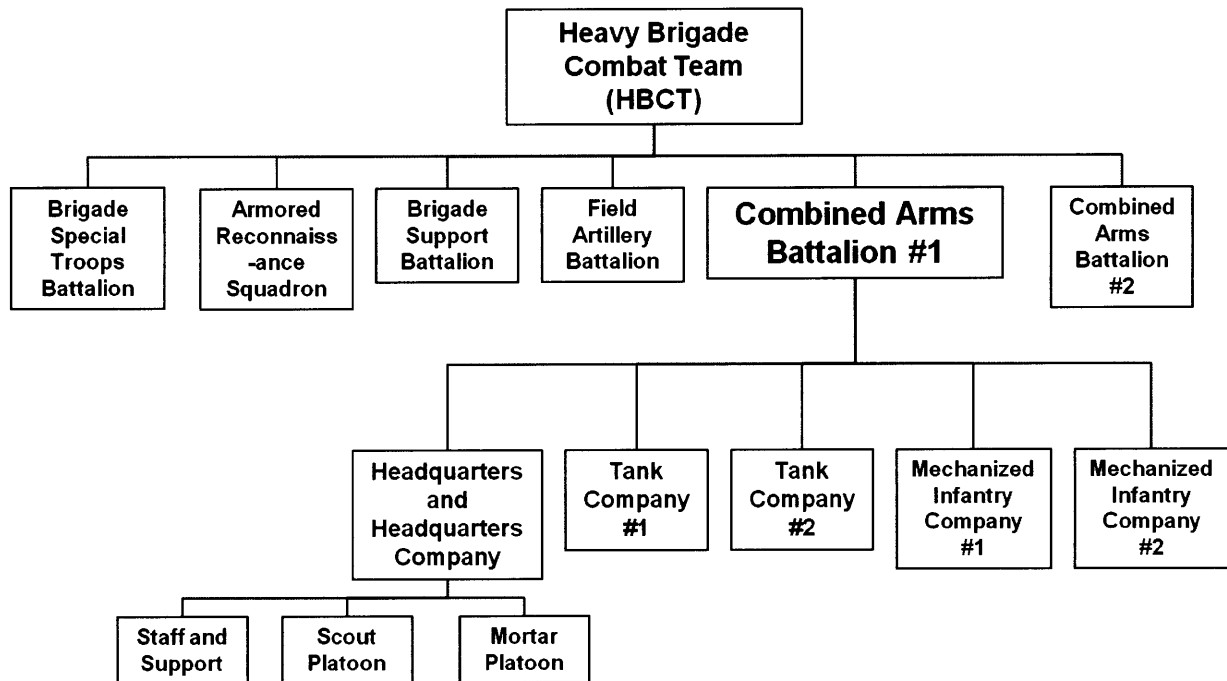


Figure 2-2: Heavy Brigade Combat Team

An infantry battalion, part of an IBCT, has a limited number of wheeled vehicles and very few of these are for combat operations. The combat soldiers in the battalion are found in three rifle companies, a weapons company, and a scout platoon and a mortar platoon in the HHC. Figure 2-3 shows the composition of an infantry brigade combat team and decomposes an infantry battalion.

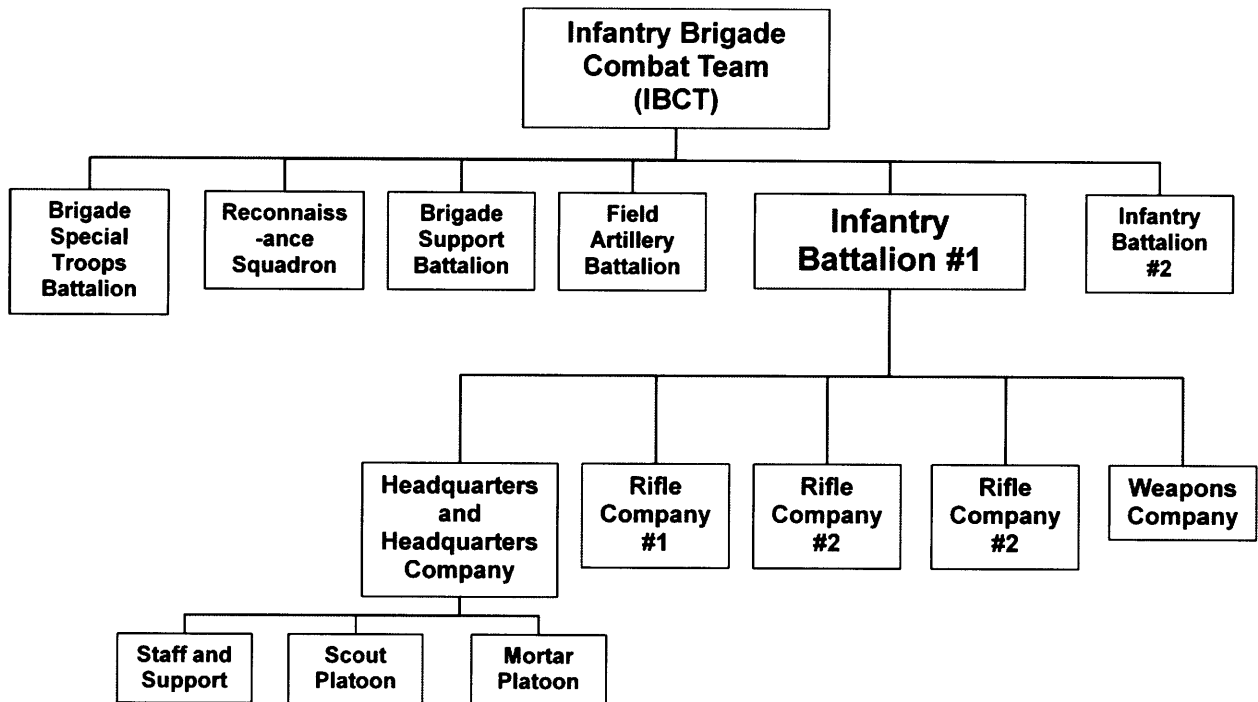


Figure 2-3: Infantry Brigade Combat Team

Table 2-1 shows the manpower in the companies in the combined arms battalion and infantry battalion.

	# of soldiers per unit	Units in Combined Arms Battalion	Units in Infantry Battalion
Tank Company	64	2	0
Mechanized Infantry Co	136	2	0
Rifle Company	131	0	3
Weapons Company	79	0	1
Headquarters (HHC) (w/o Scout and Mortar Platoons)	~170	1	1
Scout Platoon	30/22	1	1
Mortar Platoon	24	1	1

Table 2-1: Personnel Numbers by Company

2.1.2.2 Battalion Commander and his Staff

The battalion commander and his operations staff would benefit most from the research and model we present in this thesis. The commander of a U.S. Army battalion is responsible for effectively using available resources and for planning the employment of, organizing, directing,

coordinating, and controlling military forces for the accomplishment of assigned missions [3]. He delegates many tasks to his staff. The commander cannot direct and oversee everything his staff does so he provides supervision at appropriate times. Whenever an order is published, the battalion commander provides his subordinates with his guidance in a section entitled commander's intent. The commander's intent is a clear, concise statement of what the battalion must do and the conditions the force must establish to be successful ([2] 5-10).

2.2 Insurgency, Counterinsurgency, and Security

This section describes selected fundamentals of counterinsurgency that pertain to security. The Department of Defense defines insurgency as an organized movement aimed at the overthrow of a constituted government through the use of subversion and armed conflict [4]. Webster defines insurgency as, "a condition of revolt against a government that is less than an organized revolution and that is not recognized as belligerency" [5]. The Department of Defense defines counterinsurgency as the "military, paramilitary, political, economic, psychological, and civic actions taken by a government to defeat insurgency" [4]. The U.S. Army defines the end state of counterinsurgency as "a legitimate Host Nation government that can provide effective governance" [6].

These definitions, for those that have dealt with the challenges of counterinsurgency, are very concise for a vastly complex and ambiguous situation. The intricacies of counterinsurgency require careful and sophisticated thinking, deep cultural understanding, and often fundamental conceptual shifts.

2.2.1 Counterinsurgency Theory and Doctrine

There are volumes written on insurgency and counterinsurgency that outline historical examples and attempt to explain its complexities. Written in 1896, Charles Caldwell's book Small Wars: Their Principles and Practice advocated that a winning strategy to defeat an insurgency was through understanding and countering the insurgents' methods. In 1964, David Galula wrote in Counterinsurgency Warfare: Theory and Practice that the main emphasis for successful counterinsurgency lie with winning the population. His writings were based on research in Indochina and Algeria. Robert Thompson wrote in 1966 about Defeating Communist insurgency: Experiences in Malaya and Vietnam where he outlined five principles for successful

counterinsurgency. For Thompson, the key to defeating an insurgency was the host nation government's ability to organize and function. These are the "classic" theories of counterinsurgency that evolved in the Twentieth Century.

Recent conflicts such as Iraq, Lebanon, and Afghanistan, show subtle differences between the conventional counterinsurgency discussed above and the contemporary ones that nations find themselves involved in today. The conventional counterinsurgencies studied by Galula and Thompson dealt with a militant faction vying for legitimate power in a nation-state. The Vietcong trying to overthrow the South Vietnamese government and unite the peninsula under communist rule is an example of a conventional insurgency, while the contemporary counterinsurgency conflicts involve insurgents with less ambitious goals. Most insurgents in current conflicts do not want the responsibility of national governance. They prefer regional isolationism where they can govern and dispense justice without interference.

The military has published doctrine to encapsulate the challenges of conflicts that lie outside the realm of conventional war. The Marine Corps manual Small Wars Manual, published in July 1940, captured the lessons learned by the Marines in conflicts in Latin America prior to World War II. This manual served the Marines for over 60 years, including use by Combined Action Platoons in Vietnam. The Army published the US Army Handbook for Counterinsurgency Guidelines for Special Forces in 1966 but did not provide this doctrine to the operational Army. Unfortunately, the topic of counterinsurgency was largely absent from US military writings and analysis during and after Vietnam [7].

The Army released a series of field manuals that addressed non-conventional war in the 1980s and 1990s, but with little in-depth coverage of counterinsurgency. US Army Field Manual (FM) 100-20, Military Operations in Low Intensity Conflict, dates back to 1981 and was the relic of doctrine from the war in Vietnam. Stability Operations, FM 3-07, was published on February 20, 2003 – one month before the start of the conflict in Iraq. This manual replaced FM 100-20 and was a result of the military incursions in Bosnia and Kosovo.

In 2006 the United States Army, along with the Marine Corps, published a new field manual to address the situation the United States military was experiencing in Iraq and Afghanistan. FM 3-24, Counterinsurgency, summarizes theories and characteristics of counterinsurgency to provide a context for applying traditional military doctrine to the situations similar to Iraq and Afghanistan. The Army augmented FM 3-24 in March 2009 with FM 3-24.2, Tactics in

Counterinsurgency. The tactics manual reviewed many of the same topics found in FM 3-24, but went in-depth to provide best practices at the tactical level.

2.2.2 Relevant Characteristics of Insurgency and Counterinsurgency

“Success (in counterinsurgency) requires the government to be accepted as legitimate by most of [population]” ([8] 1-20). The need to bolster the host nation government and its security forces is paramount in counterinsurgency. To accept a government, the citizens must have reasonable expectations that the government can provide order or otherwise the people will seek security from other “illegitimate” sources. A legitimate government requires the people’s support over a long duration of many months or years. A simple majority of the population temporarily favoring the government is not enough to claim victory. During the period of fostering confidence in the government, the nation’s designated security forces must maintain order for the process to be successful.

Insurgencies require support and sanctuaries: shelter, supplies, and intelligence, all of which must come from the local people. Insurgents often use coercion to obtain supplies, recruit new personnel, and maintain backing for their causes. For the counterinsurgent, the primary objective is to foster development of a legitimate government supported by its citizens [8]. Insurgencies historically last many years during which insurgents are adept at using intimidation to sway and manipulate the population even when it appears the people support the government. To deny the insurgent support and protection, a crucial element in counterinsurgency is separating the insurgent from the population. The population is the acclaimed prize in counterinsurgency because it is between the insurgent and the counterinsurgent [9]. Unfortunately, identifying insurgents is very difficult as they blend with local population for safety and anonymity. The counterinsurgent agent, especially if he is foreign and does not speak the native language, has great impediments in distinguishing the insurgents from civilians.

Insurgents are usually outmatched by counterinsurgents in firepower and technology. Because of this, insurgents must choose when and where to fight in order to negate the effect of superior firepower. They often use guerilla or terrorist tactics to undermine security and to incite a counterinsurgents’ response. Counterinsurgents risk deterioration of the population’s support if their actions kill civilians or create collateral damage. Finally, insurgents are often involved in

crime and criminal activities. The kidnapping for ransoms and trafficking of drugs, weapons, or stolen goods are very lucrative and provide necessary funds for insurgent groups.

2.2.3 Security in Insurgency

In classic counterinsurgency theory, Galula states that security is the foundation for other aspects of counterinsurgency to flourish [10]. Contemporary writers agree that securing the people is fundamental to effective counterinsurgency ([11] 94). In counterinsurgency doctrine, security is a fundamental step in allowing all aspects of government and economic development to flourish ([8] 1-131).

Throughout counterinsurgency doctrine the concept of security is discussed with examples provided on what can be done to improve security; however, it is unclear what constitutes a “secure population.” FM 3-24 lists a number of general considerations for civil security operations. Two examples below address eliminating the insurgents:

- Win over, exhaust, divide, capture, or eliminate the senior- and mid-level insurgent leaders as well as network links.
- Disrupt base areas and sanctuaries.

Other considerations provide general guidance for civil security:

- Identify tasks the host-nation government and populace generally perceive to be productive.
- Consider how the populace might react when planning tactical situations and anticipate how people might respond to each operation.

FM 3-24 also advises, “To protect the populace, host nation security forces [should] continuously conduct patrols and use measured force against insurgent targets of opportunity” [8].

FM 3-24.2, Tactics in Counterinsurgency, provides specific examples of offensive, defensive, and stability operations to establish civil security and control. The offensive operations attempt to find the insurgent through search and attack; cordon and search; and patrolling. Under defensive operations, most tasks address securing physical locations or disrupting the insurgents through the establishment of bases. The stability operations’ tasks include enforcing cease fires, identifying and neutralizing potential adversaries, and finally, securing the population.

The field manual provides no further guidance or definition of what securing the population consists of. In the follow-on subsections, we attempt to define and quantify population security.

2.2.3.1 Importance of Personal Security

In 1943, Abraham Maslow defined incremental layers of needs that require fulfillment and that can explain people's motivations in life [12]. The needs at a lower level require satisfaction before higher-order needs are attended to. Figure 2-4 shows that Maslow's 'hierarchy of needs' puts security at the second level, just above physiological needs (air, water, food, shelter).

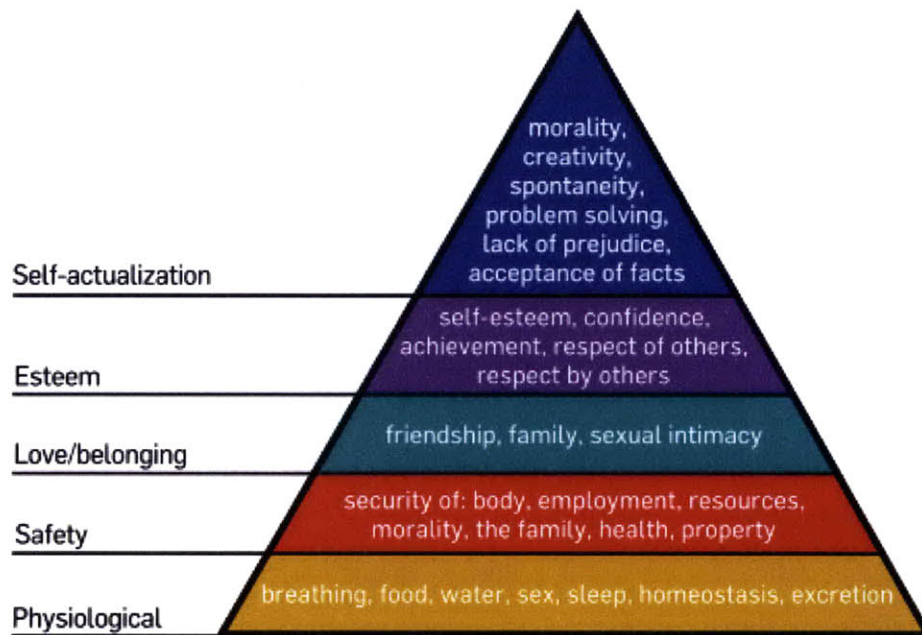


Figure 2-4: Maslow Hierarchy of Needs

Even within the layer of safety, a person prioritizes differently in traumatic situations. Financial security becomes a lower priority when one's family or own life is threatened. If the life-threatening trauma continues for weeks or months, such as in a war zone, then, "[a] man, in this state, if it is extreme enough and chronic enough, may be characterized as living almost for safety alone" [12]. Maslow's theory helps explain where security fits into the decisions of individuals or groups.

For a better understanding of security, we examine writings on security in the modern world. Security expert Bruce Schneier states, "The reality of security is mathematical, based on the probability of different risks and effectiveness of different countermeasures" [13]. Schneier also points out that security is not only reality, but also a feeling – an individual's reaction to the risks and what is being done to prevent them. Measuring the severity and the probability of the risk versus the magnitude of the costs and how well the countermeasures lessen the risk does not

accurately reflect people's perception of risk. He discusses the emotional aspect of security – times when people are secure, but do not feel secure and vice versa. He contends that security countermeasures need to be designed around the feeling of security as much as lowering the probabilities of risks [13].

2.2.3.2 Defining Population Security

The expectations of the local population are important to defining both effective and legitimate governance ([8] 1-21), and security. Security differs between and within cultures. Even in America, the level of crime acceptable for people in a city would not be acceptable for someone living in a small-town. How the people of a region define security is important to designing countermeasures for security threats. A local definition of population security depends on both the number of incidents and on how tolerant a specific people are of such incidents. A particular population's feeling of security may fluctuate depending on activities in their specific area. For instance, a homogenous neighborhood that experiences relatively low violence and has few "outsiders" passing through may judge their security as very high. One incident could shatter that feeling of security for an indefinite period.

The rule of law is critical for providing security. In general, people need to be relatively free from crime, violence, or threat of violence [12]. Additionally, if crimes are committed, the citizens want the criminals held responsible for their actions and punished accordingly.

There are a number of factors that contribute to our definition of population security. We start with the work by Maslow and incorporate Schneier's work on defining security. Additionally, we conducted a number of interviews with Army officers who recently served as battalion or brigade commanders in Iraq or Afghanistan and incorporate their characterizations of population security. The factors of population security are:

1. Level of violence: number of violent acts by type (murder, kidnapping, robbery, suicide bomb, etc.)
2. Actions of insurgents/criminals: the number of insurgents living and operating in the area and to what extent extortion or coercion occurs. Does the presence of insurgents put civilians at risk by creating a potential battle ground?
3. Inter-group conflict: contentious relationships between factions (tribe, sect, clan) within the area

4. Effective local security force: a force protecting the interests of the local population. The presence alone of host nation forces will have limited impact on security if they are judged inept. Host nation forces that are corrupt or incompetent will likely decrease the feeling of security for the population. Schneier states that people feel less fear about risks from a government or authority that they trust [13].
5. Terrain: does the geographical composition and infrastructure offer isolation or protection from insurgency and potential violence.

2.2.4 Indicators of Security

Security may be difficult to define but is even harder to measure, so how do we gauge the security of a group of people? In Iraq and Afghanistan, the number of attacks (also called security incidents) is usually the main gauge for level of coalition security, but not necessarily population security. Military analysts also measure security using casualty figures for counterinsurgents or civilians, the number of weapons caches found, and the number of security tips [14].

Various government and non-government agencies have attempted polling in Iraq and Afghanistan to gauge the level of population security. However, polling can be biased based on who is conducting the poll, where the polls are conducted, and how truthful participants feel they can be.

Doctrine lists a number of other indicators that measure a unit's success in achieving security during a counterinsurgency:

- The number of people traveling to religious services, businesses, or markets and the distance traveled
- The amount of agriculture making it to market and the distance traveled by the farmers
- The number of civilians dislocated from an area

Other informal and indirect methods often produce reliable measurements:

- Number of children playing outside [15]
- Number of children attending school [15]
- Number of government officials for a district actually living in that district [16]
- The cost to transport goods from point A to point B. These costs indicate how secure routes are [16]
- Number of IEDs reported by locals versus detonated

2.2.5 Securing the Population with a Limited Force

Military leaders must determine the size of an expeditionary force based on the mission. For a counterinsurgency that could last a number of years, military leaders must consider unit rotations when deciding on force levels. Given the immense cost of deploying soldiers and equipment, plus the need to maintain a ready force, most military operations that are non-conventional are conducted with a minimal number of forces.

At the strategic level, there is much debate on the ratio of forces required to secure a population in a counterinsurgency. The current doctrine for the US Army recommends a ratio of between 20 counterinsurgents to 1000 civilians (equivalent to 1:50) to 25 per 1000 civilians (1:40) [8]. Counterinsurgents include all host nation police and military along with US or coalition forces. Analysis of Twentieth-century conflicts show a range of ratios and outcomes based on a number of factors including the level of intensity of the conflict [17] and troops available [18]. Unfortunately, the data used for these analyses do not distinguish combat soldiers from support soldiers. Army doctrine also states that fewer combat forces require more risk to accomplish missions ([8] 1-27).

Following the 50:1 ratio (population to troops), a battalion of 700 soldiers could secure 35,000 civilians. This does not include any host nation security forces. If an area had a compliment of 700 host nation security forces (army and police), obviously the size of the potential population to be secured would double to 70,000.

The following table shows the requisite number of soldiers based on the population and the ratio of civilians to counterinsurgents. The orange band denotes the size of a battalion (500-1,000). The blue band denotes the size of a US Battalion and host nation battalion together (1,000-2,000)

	Ratio										
	10:1	25:1	40:1	50:1	75:1	100:1	150:1	200:1	300:1	400:1	500:1
Civilian Population	500	50	20	13	10	7	5	3	3	2	1
	1,000	100	40	25	20	13	10	7	5	3	2
	2,500	250	100	63	50	33	25	17	13	8	5
	5,000	500	200	125	100	67	50	33	25	17	10
	10,000	1,000	400	250	200	133	100	67	50	33	20
	20,000	2,000	800	500	400	267	200	133	100	67	40
	25,000	2,500	1,000	625	500	333	250	167	125	83	50
	35,000	3,500	1,400	875	700	467	350	233	175	117	70
	50,000	5,000	2,000	1,250	1,000	667	500	333	250	167	100
	75,000	7,500	3,000	1,875	1,500	1,000	750	500	375	250	150
	100,000	10,000	4,000	2,500	2,000	1,333	1,000	667	500	333	200
	150,000	15,000	6,000	3,750	3,000	2,000	1,500	1,000	750	500	300
	200,000	20,000	8,000	5,000	4,000	2,667	2,000	1,333	1,000	667	400
	300,000	30,000	12,000	7,500	6,000	4,000	3,000	2,000	1,500	1,000	600
	400,000	40,000	16,000	10,000	8,000	5,333	4,000	2,667	2,000	1,333	800
	500,000	50,000	20,000	12,500	10,000	6,667	5,000	3,333	2,500	1,667	1,000
	750,000	75,000	30,000	18,750	15,000	10,000	7,500	5,000	3,750	2,500	1,875
	1,000,000	100,000	40,000	25,000	20,000	13,333	10,000	6,667	5,000	3,333	2,500

Table 2-2: Counterinsurgents Based on Population and Ratio

The follow-on sections discuss approaches to providing population security to areas with limited forces.

2.2.5.1 Ink-Spot/Oil-Spot Strategy

In a September 2005 article in *Foreign Affairs* magazine, author Andrew F. Krepinevich Jr. offered a recommendation for how America needed to change its strategy in Iraq. He suggested an “oil-spot strategy.” This strategy suggested that instead of trying to kill all insurgents, forces should be allocated to secure key areas for a long duration and, as the initial area’s situation improves, expand the area – like the growth of an oil-spot or an ink-spot. He proposes a time consuming method that requires a significant commitment of forces in size and duration of deployment [19]. An oil spot strategy was not a new concept, but one that had lain dormant in military writings since Vietnam [20]. The oil-spot theory advocates the concentration of resources to a small area to make the population outside of the secure area desire the benefits of cooperating for government sponsored programs.

Other theorists and authors have written about the benefits of the “ink-spot theory” of applying limited forces to counterinsurgency. Experts contend that sprinkling troops throughout

the population is a bad strategy; instead, commanders must focus on areas critical to the enemy and the host government [21].

2.2.5.2 Clear, Hold, Build

Also in 2005, the phrase, “clear, hold, build” became common military vernacular to describe a method for confronting the challenges of counterinsurgency. The “clear” phase removes the enemy from an area, the “hold” phase maintains security with continuous security forces, and “build” phase improves the infrastructure and governance of an area. This concept supports the oil-spot/ink-spot approach.

Clearing is a task that the US Army does very well because of its similarity to the missions of conventional war. The clearing phase is usually done first. The hold and build phases are conducted simultaneously, as portions of an area are cleared. The crucial step prior to the start of any clearing operation is to adequately resource the hold and build phases with the personnel, material, and funding required to make initial and lasting impacts. The objective of this approach is to create a secure physical and psychological environment [8].

2.2.6 Securing the Force (Force Protection)

A military unit must also secure itself in order to preserve its personnel and equipment to continue the mission. The Army defines force protection as – “actions taken to prevent or mitigate hostile actions against Department of Defense personnel (to include family members), resources, facilities, and critical information. These actions conserve the force’s fighting potential so it can be applied at a decisive time and place and incorporates the coordinated and synchronized offensive and defensive measures to enable the effective employment of the joint force while degrading opportunities for the enemy” [22].

Military commanders at all levels must balance risks with benefits when determining force protection requirements. One measure to prevent and disrupt attacks on bases is to position personnel on guard at the base: guard towers, entry points, or roving the perimeter. These guards act as both a deterrent to attacks and a ready force if an attack is to occur. Greater levels of force protection usually require more soldiers on guard or actively prepared to defend the base.

Increasing force protection does not always require more manpower. Soldiers on guard can be augmented with additional firepower (larger caliber weapons) and additional surveillance platforms to mitigate risks [23]. While such measures can reduce the size of a guard force, it

cannot completely replace the need for soldiers on guard. Manpower requirements for guard duty must be balanced with the forces needed to accomplish assigned missions. More soldiers on guard-- providing better self-protection-- decrease the number available for patrol.

2.3 Recent Counterinsurgency Operation

Although we have highlighted the evolution in counterinsurgency theory and doctrine, we would like to discuss some of the events in Iraq that are the basis for doctrine, especially as it relates to population security and our discussion of combat outposts (COPs). The following section chronicles some of the challenges in population security in Iraq. It also describes how a battalion in Iraq and Afghanistan initially operates upon assuming its area of operation.

2.3.1 Iraq Early Strategy

The invasion of Iraq began on March 19, 2003, and major combat operations ceased on April 9, 2003, as Baghdad fell. In the following weeks, military leaders partitioned Iraq and assigned units to areas of operation to begin stability and support operations.

Upon the occupation of Iraq, the coalition found Iraq's dilapidated infrastructure was barely providing adequate services to its citizens, but enough to meet their physiological needs. Although Iraqis were upset at the Americans inability to quickly fix the infrastructure problems, they were even more frustrated by the lack of security. The citizens of Iraq expected the most powerful nation in the world – who had caused the abolishment of the Iraqi army and disbandment of the police – to provide security and order. As turmoil continued months after the invasion, many Iraqis lost what little confidence they had in the US-backed Iraqi government.

There were considerable differences on how U.S. units approached their new mission. Few units had trained or understood what was required to stabilize the lawless country and secure the population. Most units excelled in the conventional missions they were trained to accomplish (conducting raids or large scale clearing operations), but did not realize the impacts their aggressive behaviors were having on the population's attitude.

After the occupation began to show signs of faltering and insurgent attacks increased in early 2004, the U.S. devised a strategy to limit encounters with the population in urban areas. The military in April 2004 was to pull back from the cities and consolidate on large Forward Operating Bases (FOBs). At that time, there existed varying sized FOBs throughout the country

of Iraq, some housing over 20,000 soldiers. This shift in strategy was based on the belief that the presence of US forces' was the main cause of violence and attacks in Iraqi cities. The logic was that if the coalition removed the foreign security forces, both the insurgents' desire and opportunity to attack would diminish.

Unfortunately, this was woefully mistaken. Although America forces found relative safety inside these sprawling FOBs, the units still needed to conduct patrols into cities. This provided insurgents a number of advantages. First and foremost, the Americans were seen as providing part-time security. Patrols would come into an area and leaders would promise protection and security, but would eventually depart, leaving behind the civilians at the mercy of the insurgents. US forces patrolled from central locations – allowing insurgents the ability to observe and monitor. In many neighborhoods, terrain restrictions made movement into and out of locations difficult except for one or two routes. This gave insurgents early warning and made the American's movement very predictable. As this strategy was implemented at the tactical level, the violence between religious factions increased while the Iraqi people's support of their new government decayed.

2.3.2 The Surge in Iraq

In January 2007, the President ordered an increase in the number of combat soldiers in Iraq for a one year period to establish conditions that would allow the Iraqi government to flourish. Military and government leaders deemed Baghdad the center of gravity for stabilizing and securing the country of Iraq. If the capital could not be controlled, what hope did the rest of the country have? The use of the "clear, hold, build" became the guidance for securing the capital and its population. The number of soldiers in Baghdad increased significantly to 30,000 US troops and an equal number of Iraqi security forces [24]. Units now had the personnel to adequately man and patrol from numerous outposts within the neighborhoods in Baghdad and other major cities.

2.3.3 Battalions Operating in Counterinsurgency

A battalion commander and his staff encounter a number of challenges when assuming an area of operation (AO) in a counterinsurgency operation. A battalion will be given a specific AO, guidance, and a mission with emphasis on providing security. The size of a battalion AO in

counterinsurgency will vary given the total forces deployed compared to the total land area of the theater of operation. When determining the size of AOs, planners consider population density, terrain features, and strategic importance. Baghdad is a city of six million and might include a dozen battalion areas, some only consisting of a few square miles of dense buildings. However, a battalion might be assigned tens of thousands of square kilometers where a vast majority is uninhabitable desert. Al Anbar is Iraq's largest province but 95% of it is desert, with the population concentrated along the Euphrates River. In such an area, a battalion may be assigned an "economy of force" mission and given an extremely large area, in size and population, but is expected to accomplish significantly less.

The battalion commander must decide how best to utilize his forces to accomplish their mission. One very common and effective way to ensure coverage is to parcel the battalion AO into four smaller sections and assign one of his combat companies to each section. Each company will operate almost exclusively in its company AO so that its soldiers become intimately familiar with the terrain and the people. The company conducts a variety of missions within the guidance of the battalion commander.

In counterinsurgency, both the combined arms battalion and infantry battalion are augmented with wheeled vehicles such as up-armored high-mobility, multi-wheeled vehicles (HMMWV) or mine-resistant, ambush protected (MRAP) vehicles that to allow units to transverse the battlefield.

The battalion commander must also decide where to base his soldiers, by considering his mission, the terrain, the enemy, the population, but also the safety of his soldiers. The battalion can consolidate in one FOB or even share a FOB with an entire brigade. As will be discussed later, the use of smaller combat outposts (COPs) allows a number of advantages but at a cost. For a stabilizing force arriving immediately after an occupation, there are probably many options for the commander to position his soldiers. However, once units begin rotating, a relieving unit is initially constrained to the bases and outposts established by the departing unit.

The choice of headquarter location depends on the commander's preference. The battalion commander may want to position the HHC in a provincial capital, near a host nation headquarters, or possibly centrally located in the AO. With company headquarters, the battalion AO may get segmented into company areas of operation and the company headquarters will have to set up in a COP within the company AO.

2.3.4 Training Host Nation Forces in Counterinsurgency

We include a description of transition teams to familiarize the reader with supplementary units involved in host nation forces training, but we do not explicitly represent transition teams in our model. The Army and Marines began forming ad hoc “transition teams” for training and rebuilding the army and police of Iraq and Afghanistan in 2003. The teams are comprised of 12-15 soldiers and are assigned to the host nation battalion, brigade, or division. Through the end of 2009, transition teams were separate from the battalion operating in a specific area of operation. The transition teams work with the leadership of the host nation security forces, but lack the personnel to closely interact with and train the lower ranked soldiers. However, American battalions conducting combined patrols with host nation security forces have an opportunity to conduct “on-the-job training” and mentoring as they patrol. Even with limited interpreters, the soldiers from the battalions can be role models for conducting effective security operations.

2.4 Combat Outposts

This section examines combat outposts (COPs) and how they became part of counterinsurgency doctrine for the Army. We give the reader a better understanding of decisions in COP locations and sizes.

Combat outposts are defined in the July 2001 publication of FM 3-90, Tactics, as a reinforced observation post capable of conducting limited combat operations. This FM advises that a COP is typically occupied by a reinforced platoon, is organized to provide an all-around defense to withstand a superior enemy force, and can facilitate aggressive patrolling ([25] 12-33). FM 3-90 was written for the context of conventional warfare.

2.4.1 COPs in Counterinsurgency

Neither the term COP nor the idea of an outpost appears in the 2006 publication of FM 3-24. The follow-up field manual, FM 3-24.2, describes in detail the significance of COPs. “[COPs] are a cornerstone of counterinsurgency operations, in that they are a means to secure the population” [6]. A COP provides security for the surrounding area and facilitates continuous contact with the local population. COPs in Iraq and Afghanistan are semi-permanent or permanent structures that protect against attacks and allow for extensive patrolling in populated areas.

FM 3-24.2 lists the military purposes of COPs as:

1. Secure key lines of communication or infrastructure
2. Secure and co-opt the local populace
3. Gather intelligence
4. Assist the government in restoring essential services
5. Force insurgents to operate elsewhere ([8] 6-9)

Additionally, COPs provide better protection of the populace, enable greater freedom of movement, and enable soldiers to better interact with the local population [23]. The location of a COP gives soldiers an increased ability to enforce the law and maintain order. LTC Dale Kuehl writes of his experience in northwest Baghdad and how their COPs disrupted the freedom of movement of Sh'ia militia and Al'Qeda [26]. He says the constant observation and numerous daily interactions with the populace allow the soldiers to better understand the local citizens and their needs. A COP located in the middle of a residential area permits the local citizens greater opportunity to report suspicious activities without the fear of retribution from insurgents.

The continuous presence of US and host nation forces in a COP provide an improved level of security for the area. To build rapport, the local population must believe that the security forces will stay for a long duration and will not abandon the area. A COP signals a high level of commitment that security forces have for the area. Contrary to patrols that come and go, a COP indicates to the local population a dedication to security. After the security forces show the fortitude to remain at a location, even following insurgent attacks, the locals slowly begin to develop trust and confidence in security forces. COPs can be analogous to a local police station. Research in criminology supports the notion that the observable presence of police has a large deterrent on crime in an area. This research showed that effect was localized to only the area the police deployed [27]. If the soldiers are able to allow the local population to function as they wish, the locals will accept a small inconvenience of having the soldiers (as long as the actions of the soldiers do not cause further hardships for the locals).

Furthermore, operating out of numerous COPs decreases travel time for patrols compared to the whole battalion departing from one central base. Departing from multiple points makes tracking patrols more difficult and gives security forces an added element of surprise. COPs spread across the area of operations are also used for greater command and control in Iraq [26].

2.4.2 COP Size

COPs are usually company or platoon-sized. A platoon ranges in size from 16 to 40, while a company ranges in size from 65 to 150. An article in the December 2008 issue of Army published former deployed company commanders' opinions on the minimum number of soldiers required to reasonably occupy and defend a COP in combat [28]. Responses varied, but a majority felt that a platoon (or roughly 20-30 soldiers) was the minimum that could adequately defend a COP in case of an attack.

In a survey conducted by the author from August to September 2009, company grade officers were asked about their experience executing COPs in combat. The average number of US forces in a COP in Iraq was 27. For Afghanistan, the average numbers of US were 35.

2.4.3 COP Locations

Doctrine states that COPs are often located in insurgent-influenced areas, commonly the middle of neighborhoods [6]. COPs are often collocated with host nation security forces, either sharing the same building or within the same compound. Basing US soldiers in close proximity to host nation forces allows continuous coordination and improved partnership. COPs with both US and host nation forces are often referred to as Joint Security Stations (JSS).

In Iraq, the use of abandoned government buildings or former Ba'ath Party Headquarters was ideal because of their solid construction and their location next to police stations in the center of towns. Other abandoned buildings in urban centers were also very effective as a COP, because they were well constructed to provide a certain amount of protection from the enemy's weapons. US forces used concrete barriers for additional protection and emplaced concertina wire to produce stand-off and control entry to the COP. For a well planned occupation of an existing building, the emplacement of barriers could be done in a matter of hours and a COP could be occupied and operational in less than a day.

Outside of urban areas, as often experienced in Afghanistan, US forces have few reliable structures but greater flexibility in where to locate COPs. If suitable buildings were not available, US forces might have to construct the entire outpost. US forces can create a COP in an open field on the outskirts of a village by emplacing tents for living areas and using earth barriers to fortify. Building an entire COP takes considerably longer (possibly weeks) and requires extensive building material and construction equipment.

Outposts are often established to be mutually supportive so that soldiers from another outpost can quickly respond to an attack at a neighboring outpost. This is sometimes only viable in urban areas; some COPs can be very remote and isolated from other bases.

2.4.4 How Commanders Determine COP Locations

FM 3-24.2 advises commanders to closely analyze a sector to determine the task and purpose of a potential COP, before determining its location [6]. COPs are often located in dense population centers, especially symbolic locations such as provincial capitals or business districts. Some commanders place a COP in the middle of the worst insurgent area for a disrupting and psychological effect. This placement communicates to the local population that the Army will not be intimidated or controlled by the insurgents. Setting up in insurgent-controlled area also diminishes the public's perception of insurgents' power. Commanders can expect immediate attacks on a new COP if the location is important to the insurgents [15].

Also, commanders emplace COPs on main insurgent routes. A new outpost with active patrolling will disrupt insurgents' freedom of movement and increase the insurgents' possibility of getting captured. One captain recently deployed to Iraq advises consideration of both security (force protection) and social impact when choosing a location. Army personnel are very attuned to the security issues (ability to defend, ability to resupply, ability to support) but often neglect the importance of the population. He recommended not using public works facility. Although utility plants might require guarding by US soldiers, such plants are often insurgent targets. The presence of a large number of soldiers makes public works even more appealing for attack. Any damages that disrupt services will likely be blamed on US soldiers and cause great animosity among the people [23].

Finally, other commanders choose locations between clashing factions. In Iraq in 2006, when sectarian violence was the highest, one commander had an area of operation containing two warring religious sects. A cycle of violence ensued as retribution for attacks on one side were quickly followed by retribution on the other side. The neighborhoods housing the two sects were distinct and separated by a major roadway. To prevent the ease of access to the opposing neighborhood, the commander ordered a COP with a traffic control point established between them. The COP disrupted the movement of roving death squads into the opposing neighborhood

and greatly reduced violent activities [29]. This supports the strategy to separate fault lines between warring factions in counterinsurgency [30].

2.5 Future Conflicts

Future conflicts for the United States military will likely resemble the recent experiences in Iraq and Afghanistan. Terrorists, probably one of the leading threats to national security, use unstable regions and countries for their sanctuary. There is little expectation insurgent warfare will diminish given its relative success. Future enemies would look to negate the technological advantage of the US military by continuing insurgent tactics.

2.6 How We Can Help Commanders and Their Staffs

The COP, in the current counterinsurgency environment, has found its rightful place as a success story and one that will likely be repeated if America finds itself in another insurgency. There are many factors for a commander and his staff to consider when deciding how and where to operate in a counterinsurgency. The ability to account for and synthesize all facets of a situation is daunting.

In the follow-on chapter, we create a model that describes and integrates relevant inputs from an area of interest. The model allows the commander flexibility to modify specific weights so the model corresponds to his circumstances. We create an algorithm to measure population security that specifically scrutinizes reduction of violence, reduction of insurgent activity, and improvement of host nation force effectiveness. By incorporating improvement of population security, the algorithm recommends the location and size of COPs and patrols for a set of given conditions. The model will provide the commander and staff with outputs to visualize a solution and understand where the improvement in population security will likely occur.

3 MODEL & FORMULATION

This chapter describes the mathematical model to measure population security and our algorithm to maximize security improvement. We begin this chapter by describing how a battalion area of operation is represented as a network, which facilitates creation of a mathematical model. We then present the variables, parameters, and constraints of the model. Finally, we explain the formulation of the objective function. Throughout this chapter we address the assumptions made to make the problem more tractable.

3.1 Modeling the Area of Operation

The geographic relationship of an area of operation is represented as a network consisting of nodes and arcs. A node represents a neighborhood, town, city, or possibly a grouping of villages and is a candidate location for a combat outpost. There is no prescribed standard of what constitutes a node. The size of a node, in both land area and population, depend on how a commander segments his area of operation. In general, we recommend a node should have at least a population of 1,000. A medium size city (50,000 – 150,000) may be one node or multiple nodes depending on the population density and if a reasonable partitioning exists. Metropolitan areas can be decomposed using established neighborhoods. Creating nodes in rural areas is more problematic because small villages may be difficult to rationally group together. Not every citizen will be counted in an area of operation. People living in very rural areas, villages, or small towns not near a node are absent from any node population count.

The nodes are connected by arcs or edges. An arc represents an adequate road linking two nodes. We define an adequate road as one that can support the weight and width of up-armored wheeled vehicles such as the high mobility multi-wheeled vehicle, HMMWV, or the mine-resistant ambush protected, MRAP. All arcs are assumed to be undirected; a vehicle can travel from node 1 to node 2 and from node 2 to node 1. If an arc does not exist between two nodes in the network, there is not an adequate road between the two nodes. Foot trails or paths, often referred to as “goat trails,” usually cannot accommodate the military vehicles and are not represented.

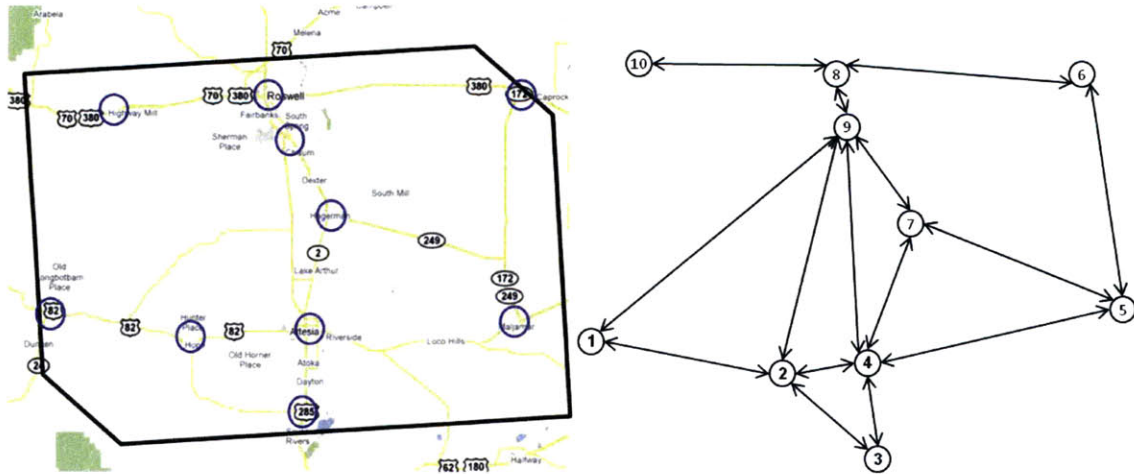


Figure 3-1: Example Graph of 10 Node Area of Operation

Figure 3-1 shows how the example area of operation (Figure 1-1) is represented using 10 nodes.

The length of each arc is the actual route distance measured in kilometers. Furthermore, all routes are classified into one of 4 categories, each with an associated speed.

- Category 1 - a single lane dirt road with an average speed of 15 km/h
- Category 2 - a single lane improved road with an average speed of 25 km/h
- Category 3 - an improved two lane highway with an average speed of 35 km/h
- Category 4 - a multiple lane highway with an average speed of 45 km/h

We assume that each node in the network is a potential combat outpost (COP) location for only one COP. Additionally, we assume the speeds listed above are relevant for all counterinsurgents' vehicles. Communication requirements and restrictions are not represented in the model; we assume perfect communication throughout the network no matter the distance or topography.

3.2 Variables

The model includes five decision variables and four dependent variables.

3.2.1 Decision Variables

The five decision variables in the model determine where soldiers operate and which node has a COP.

1. x_i^f = number of combat soldiers assigned force protection duties at node $i \forall i$

2. x_{ik}^p = number of combat soldiers based in a COP at node i that patrol in node $k \forall i, k$
3. $y_i \in \{0, 1\} = 0$ without a COP; 1 with a COP $\forall i$
4. $hhc_i \in \{0, 120\}$ = number of support soldiers from HHC based at node $i \forall i$
5. $cohq_i \in \{0, 15\}$ = number of support soldiers from company headquarters based at node $i \forall i$

All 120 soldiers from the headquarters and headquarters company (HHC) must be based together at a single node; all other nodes will have 0 soldiers. Additionally, each of the four company headquarters must be emplaced as a unit (consisting of 15 soldiers) at a single node. More information on decision variable 4 & 5 will be discussed in section 3.4.1.

The model assumes that each soldier can patrol in only one node per day.

3.2.2 Dependent Variables

There are a number of dependent variables that are used in the model.

1. x_i = number of combat soldiers (patrolling and force protection) based at node $i \forall i$

$$x_i = x_i^f + \sum_{k=1}^K x_{ik}^p \quad (3-1)$$

2. $supp_i$ = number of support soldiers from HHC and company headquarters based at node $i \forall i$

$$supp_i = hhc_i + cohq_i \quad (3-2)$$

3. v_i = number of total soldiers (combat and support) based at node $i \forall i$

$$v_i = x_i + supp_i \quad (3-3)$$

4. $pHours_i$ = number of patrol hours per day for node $i \forall i$

The calculation of $pHours$ will be discussed in detail in section 3.5.3.3.

3.3 Parameters

The model uses data that characterize the conditions of the area of operation. These parameters are divided into 3 groups: global parameters, nodal parameters, and initial conditions.

3.3.1 Global Parameters

There are 4 global parameters that pertain to all nodes and are set prior to executing the model:

Duty day of the average soldier: $dutyDay$

The soldier's duty day includes the total amount of time a soldier is on patrol or guard. It does not include the time required for patrol preparations or after operations activities. The length on a duty day for the soldiers, *dutyDay*, has a default setting of 8 hours.

The commander's level of risk: p

This parameter entails the commander's attitude to risk with respect to the size of guard forces. A commander that is risk averse will require additional guards to protect the force, while a commander with a high level of risk will require fewer guards. In reality, a commander may not be a good judge of his own attitude to risk. To determine a commander's level of risk one might compare his force protection requirements to other commanders. Commander's level of risk, p , is categorized as **low**, **medium**, or **high**, and is important for determining guard force requirements.

The civilian to counterinsurgent ratio: $ccRatio$

The parameter $ccRatio$ is the ratio of civilians to 1 counterinsurgent required for successful counterinsurgency operations. Doctrine proposes a guideline of 50:1 ($ccRatio = 50$), the default setting. This parameter can take on any continuous positive value.

Minimum number of combat soldiers per COP: m

Any node that is selected to emplace a COP must have m combat soldiers. The default for m is 25 combat soldiers.

3.3.2 Nodal Attributes

Each node has the following data:

Population: $nodePop$

Population includes all indigenous people in and around a node location. Ideally we would have an accurate count of a city or district but in many countries data is scarce or inaccurate. When accurate figures do not exist, population is estimated and rounded to the nearest 500. Since nodes often represent a conglomeration of small towns or villages, reliable estimation can be challenging. Villages or small towns not near a node are absent from any node population count.

Patrolling host nation security forces (daily average): hr^p

Not all host nation security forces are included in the model. For each node, we utilize the average number of security forces patrolling per day, hr^p . Patrol duties for host nation forces

consist of any tasks away from a base or police station to include manning check points. In practice, the number of host nation forces patrolling may be one quarter of the total assigned because of internal guard requirements, priorities of work, and liberal leave policies.

The model assumes that host nation security forces are already conducting some patrolling prior to our unit's arrival (to be addressed in section 3.5.3). We also assume the number of host nation forces patrolling at each node is constant and will not change; host nation forces are not repositioned to another node, nor increased in overall size.

COP Quality: *copQual*

copQual is judged on a combination of two factors that impact guard requirements:

1. The surrounding terrain – the relationship of the COP location to high ground and amount of unobstructed area around the structure. A COP on the top of a hill with unobstructed visibility in all directions for over two miles will have a high rating. A COP surrounded by tall buildings, only a few meters apart, will have a low rating.

2. The physical size of the structure or compound – the total area of the outpost. A smaller compound is easier to defend and requires fewer guards to observe 360 degrees.

We assume that each potential COP location has adequate walls and overhead cover for protection or it can be improved with readily available materials.

Table 3-1 shows how *copQual* is assessed on a three point scale, 1-3, 1 being the highest quality, using the two factors:

		TERRAIN		
		High ground, open area	Medium	Low ground, closed area
SIZE	Small	1	2	3
	Medium	1	2	3
	Large	2	3	3

Table 3-1: COP Quality

The table shows that a small or medium COP on high ground and open fields of fire has the highest rating of *copQual*.

3.3.3 Initial Conditions at Nodes

Each node has initial conditions that are used as parameters for our model. We assume historical data exists at each node on all of these parameters:

- Initial level of attacks: *attacks*
- Initial level of violence: *violInitial*
- Initial effectiveness of host nation forces: *effInitial*
- Initial level of insurgent activities: *insurgActInit*

We use these inputs because we assume recent insurgent behavior is an adequate predictor of their future behavior.

In our formulation, we require a single number for each parameter of initial condition (violence, attacks, insurgent activities, and effectiveness). These four parameters are quantified on a continuous scale of 0-1, 0 being the lowest level. We do not provide an exact formulation for calculating the measured values of these parameters. The computation of each parameter would be established based on the conditions in the theater or region. In combat operations, violence and attacks are recorded, analyzed, and reported by type and frequency [14]. In general, we propose the recent history of violence and attacks would be converted into a single number using a formulation to represent initial levels. Host nation force effectiveness and insurgent activities are more challenging because of the inconsistent data collected, but would require a similar methodology.

Initial Level of Attacks

The level of attacks, *attacks*, is measured by the types, number, and severity of direct action contact against security forces (both American and host nation security forces). The types of attack include, but are not limited to: roadside bomb, suicide bomb (car or individual), sniper, mortar or rocket, direct fire ambush (machine guns and rocket propelled grenades). Attacks can vary in severity. An ambush may involve only a few insurgents firing randomly and quickly departing, or it can be a well planned and well organized assault by hundreds of insurgents. Again, we do not provide an exact formulation for calculating the level of attacks. Levels of attack are measured on a unit-less and continuous scale of 0-1. A node with a 0 would be free of attacks while a node with a 1 would be the most dangerous node in the region or theater.

Initial Level of Violence

Violence is distinguished from attacks based on the intended victim: civilians vs. security forces, respectively. Examples of hostile acts used to measure initial violence, *violInitial*, include murder/execution, kidnapping, robbery, and rape. The level of violence captures general criminal behavior and the violent outbreaks stemming from feuds that exist between clans, sects, or tribes. We do not provide an exact formulation for calculating the level of violence, but such a measurement would account for the types of violent acts and their frequency. The level of violence is measured on a unit-less, continuous scale of 0-1. Similar to attacks, a node with an initial level of violence of 0 would contain no violent attacks while a node with a 1 would be the most violent node in the region.

Initial Effectiveness of Host Nation Security Forces

The parameter related to host nation forces patrolling, hn^p , is the effectiveness of the security forces, *effInitial*. This could be an ambiguous concept to assess because cultural differences make measuring effectiveness difficult. For our model, the effectiveness of host nation security forces is measured on a unit-less, continuous scale of 0-1 based on their ability to conduct area security as defined by Field Manual (FM) 3-90 or Joint Publication (JP) 3-10. We do not provide a formulation for translating a host nation force's ability to conduct an area security mission into an effectiveness rating. A host nation force with a value of 1 is effective enough to secure the entire node, while a force with a 0 is completely ineffective.

In practice, the effectiveness of host nation security forces is evaluated by a transition team assigned to the host nation organization or the U.S. unit assigned to the area. In the model, we assume host nation security forces have the potential to be as effective as US soldiers.

Initial Level of Insurgent Activities

We propose the level of insurgent activities, *insurgActInit*, encompasses all non-violent insurgent activities in the node. This parameter measures how frequently insurgents are at a node and what activities they execute while there. It evaluates the amount of support the insurgents are receiving and the means in which they attain it.

insurgActInit is based on the intelligence gathered on the node. We do not provide an exact formulation for calculating the level of insurgent activities but it would encompass all intelligence that exists at each node. A high score would indicate that a node is a safe-haven or

base for insurgents where the local population is being coerced. A score near zero indicates a node free of insurgents.

3.4 Constraints

The model includes mathematical and operational constraints.

3.4.1 Troop Allocations

The total number of troops allocated across the area of operation cannot exceed the total number of troops in the unit, n . Additionally, there are constraints on the number of soldiers of specific type: combat and support, as shown in Table 3-2. In the model, support soldiers in headquarters and headquarters company (HHC) and company headquarters (CO HQ) do not patrol or conduct guard so they are tallied separately.

Unit	Total Soldiers (n)	Combat Soldiers	Support Soldiers	
Combined Arms Battalion	630	450	180	HHC 120
				CO HQ 15 (x4)
Infantry Battalion	690	510	180	HHC 120
				CO HQ 15 (x4)

Table 3-2: Troop Allocations in the Model

We allocate 630 soldiers to the combined arms battalion. Of those 630, 450 combat soldiers are available for patrol or guard. This total subtracts the 180 headquarters staff and support personnel in the HHC (120) and the combat companies (15 per company). For the infantry battalion, we used 690 troops with 510 available for patrol (subtracting the 180 support and staff personnel).

The troop allocation constraints are listed in equations 3-4 – 3-6, given the total number of troops in the unit is n :

$$\sum_{i=1}^I v_i \leq n \quad (3-4)$$

$$\sum_{i=1}^I hhc_i = 120 \quad (3-5)$$

$$\sum_{i=1}^I cohq_i = 60 \quad (3-6)$$

$$v_i \leq ny_i \quad \forall i \quad (3-7)$$

Equation 3-7 is a basic constraint in a facility location problem so only nodes that establish a COP can base soldiers.

3.4.2 Minimum Manning

For overall security, the commander will specify the minimum number of combat forces, m , that he is willing to emplace at a single COP.

$$x_i \geq m y_i \quad \forall i \quad (3-8)$$

3.4.3 Force Protection Requirements

Each COP requires a level of force protection contingent on the commander's level of risk and the characteristics of the node's COP location. A commander who is willing to take greater risks will have a lower level of force protection. Force protection, $forPro$, represents the number of guards in a 24 hour period and is a function of commander's level of risk, p (section 3.3.1.2) and COP vulnerability, $copVuln$.

$copVuln$ indicates the difficulty in defending a COP. It is a function of $copQual$, $attacks$, and $insurgActInit$. Equation 3-9 is the calculation for $copVuln$.

$$copVuln_i = 3 \times copQual_i + attacks_i + insurgActInit_i \quad \forall i \quad (3-9)$$

$copQual$ is three times as important as the initial levels of attacks and insurgent activities when computing the $copVuln$.

For calculating $copVuln$, we transform the continuous values of $attacks$ and $insurgActInit$ into integer values using three bins shown in Table 3-3. The values of $copVuln$ range from 5-15.

<i>insurgActInit</i> or <i>attacks</i>	Integer Value
0 -0.333	1
0.334-0.666	2
0.667-1	3

Table 3-3: Bins for Transforming *insurgActInit* and *attacks*

$forPro$, or guards required for a 24 hour period, is determined by Table 3-4:

		<i>copVuln</i>										
		5	6	7	8	9	10	11	12	13	14	15
Commanders Risk Levels	High	6	6	9	9	12	12	15	15	15	18	18
	Med	12	15	18	21	24	24	24	27	27	30	30
	Low	24	27	30	33	36	39	42	45	48	51	54

Table 3-4: Force Protection Look-up

The table values for *forPro* were determined from survey data from Army officers. In the model, the guard size is independent of the total force occupying the COP. Equation 3-10 constrains the number of soldiers assigned guard duty to be equal or greater than the guard requirement for nodes that have a COP.

$$x_i \geq \text{forPro}_i y_i \quad \forall i \quad (3-10)$$

3.4.4 Calculating Ground Time

The length of time a soldier is on patrol is constrained by the travel time between nodes and the duty day length. A soldier based at one node (A) and patrolling at another node (B), must travel from A to B and back within the duty day. All patrols must start and end at the same base. These restrictions prohibit overnight patrols or patrols starting at one node that finish at another node.

A number of matrices (each matrix size is # of nodes by # of nodes) are set up to help calculate patrol hours:

- A distance matrix, **D**, displays the distance in kilometers between neighboring nodes (nodes connected by an arc) and consists of entries d_{ik} , distance from node i to node k . The d_{ik} entries for nodes that are not connected (no adequate route exists between the nodes) are zero.
- A route category matrix shows the type of routes between neighboring nodes with integer values of 1-4. The cells in the distance matrix that are zero will also be zero in the route matrix.
- The route category matrix is transformed into a speed matrix, **U**, based on the route speed (section 3.1).
- The distance matrix is multiplied by the speed matrix to calculate an arc travel time matrix, **A**. The arc travel time matrix includes all travel times between neighboring nodes.

$$\alpha_{ik} = d_{ik} * u_{ik} \quad (3-11)$$

Figure 3-2 shows the arc travel times for the example scenario presented in the introduction.

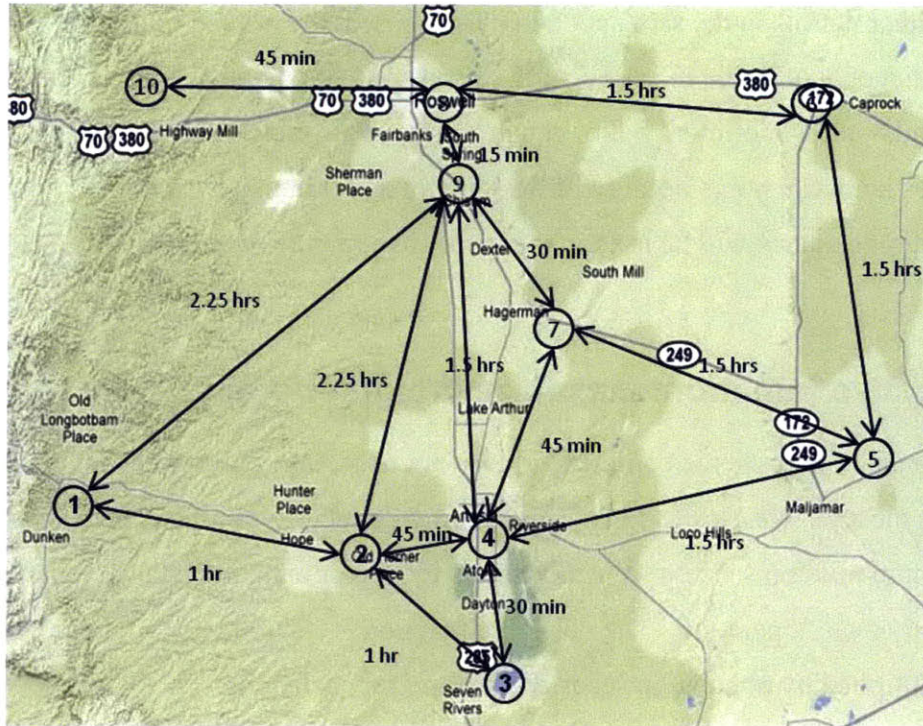


Figure 3-2: Arc Travel Times for Example Scenario

- The shortest travel time matrix, T , includes the shortest path between all pairs of nodes, τ_{ik} , determined by applying Dijkstra's algorithm to the arc travel time matrix, A .
- The ground time matrix, G , subtracts travel to and from the patrol from the duty day (Equation 3-12), and is shown in Table 3-5 for the example problem.

$$g_{ik} = \text{dutyDay} - 2 * \tau_{ik} \quad (3-12)$$

	1	2	3	4	5	6	7	8	9	10
1	8	6	4	4.5	1.5	0	3	3	3.5	1.5
2	6	8	6	6.5	3.5	0.5	5	3.5	4	2
3	4	6	8	7	4	1	5.5	4	4.5	2.5
4	4.5	6.5	7	8	5	2	6.5	5	5.5	3.5
5	1.5	3.5	4	5	8	5	5	3.5	4	2
6	0	0.5	1	2	5	8	3.5	5	4.5	3.5
7	3	5	5.5	6.5	5	3.5	8	6.5	7	5
8	3	3.5	4	5	3.5	5	6.5	8	7.5	6.5
9	3.5	4	4.5	5.5	4	4.5	7	7.5	8	6
10	1.5	2	2.5	3.5	2	3.5	5	6.5	6	8

Table 3-5: Ground Time Matrix for Example Scenario

When a soldier patrols in the same node that he is based, the ground time is maximized (as shown in the diagonal of Table 3-5). The table also shows that node 6 is particularly isolated – only node 5 and 8 allow 5 or more hours of patrol time. Patrolling in node 6 from node 1, or vice versa, produces no patrol hours because of the lengthy travel time between these two nodes.

The ground time matrix will be used in the model to compute patrol hours, *pHours*, in section 3.5.3.3.

3.5 Objective Function: Maximize Weighted Population Security

When setting up outposts, the commander does not necessarily want to provide the most security to the most people. Instead, he wants to provide security for the areas that are deemed most important to mission success. We model this by maximizing the total weighted population security for our area of operation. The objective function is a summation of commander's node weight, w_i , multiplied by population security, *PopSec*, for each node:

$$\max \sum_{i=1}^I w_i \text{PopSec}_i \quad (3-13)$$

Where:

$$\sum_{i=1}^I w_i = 1 \quad (3-14)$$

Default node weights are set proportionally to the population. If the commander delegates the node weights to his staff, they will need to interpret his commander's intent and adjust appropriately. Reasons to increase the node weight may include: the node is the provincial or district capital, the node lies along a main highway or supply route, or the node is the first town after a border crossing where he believes insurgents are infiltrating.

PopSec is comprised of three elements, each which contributes to a population's perceived level of security and will be described in detail in follow-on sections:

- Security by reducing violence: sec^v
- Security by reducing insurgent activities: sec^{insurg}
- Security from confidence in host nation forces: sec^{hn}

Based on discussions with former battalion and brigade commanders, these three elements encompassed how they defined security. Other elements of population security were considered but discarded because they had significantly less impact on overall security of the population.

PopSec is a summation of commander's security weight, c_j , multiplied by an element of security:

$$PopSec_i = c_1 sec^v_i + c_2 sec^{insurg}_i + c_3 sec^{hn}_i \quad \forall i \quad (3-15)$$

$$\sum_{j=1}^3 c_j = 1 \quad (3-16)$$

The commander sets the weight for the three elements of security based on their perceived importance to the local population and his ability to accomplish his security mission. The two commander's weights, node and security, allow the commander the flexibility to customize the model to his specific circumstances.

3.5.1 Security and Violence

The biggest contributor to instability and insecurity in an insurgency is likely violence. The absence of a strong government allows power to shift to those willing to use violent means without fear of repercussions. To be successful in securing the population, the government and the counterinsurgent must reduce the violence.

3.5.1.1 Reducing Level of Violence

Violence is reduced at a node by increasing the number of patrol hours per day.

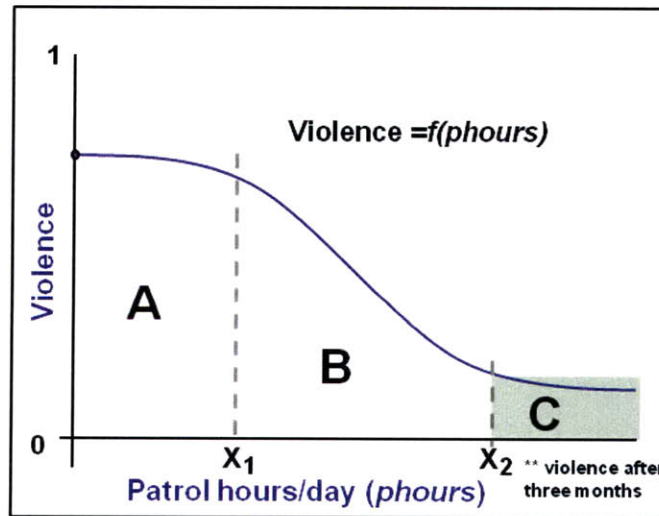


Figure 3-3: Violence vs. Patrol Hours per Day

Figure 3-3 depicts how the level of violence typically relates to number of patrol hours per day. This function is an amalgamation of experiences of deployed Army officers who were surveyed and interviewed for this research.

Initially, a small number of patrol hours per day will be unable to curtail violence, shown as region A in the figure. With a sufficient increase in daily patrol hours, the unit covers more area, remains in the area for longer periods of time, and interacts with more of the local residents to better understand the situation. This is represented by region B in the figure. At x_1 and greater, an additional patrol hour has increasingly more violence reduction. Eventually the patrol hours' impact on violence experiences diminishing returns. In the second half of region B, an additional patrol hour continues to reduce violence but at a declining rate. Finally, the node is sufficiently patrolled and steady-state violence is reduced to a stable level but not eliminated. The adding of more patrol hours provides little or no reduction in the level of violence as shown in region C.

In the model, individual US soldier's capabilities are not distinguished. It assumes all US soldiers are the same and does not account for rank, experience, or training. Additionally, the model does not distinguish patrol activities.

3.5.1.2 Security versus Violence

Our model proposes an inverse linear relationship between population security and the level of violence. Level of violence is measured on a 0-1 scale, as is security. Security by reducing violence (sec^v) increases by reducing violence:

$$sec^v = 1 - violence \quad (3-17)$$

sec^v is best described as a positive logistics function with an asymptote at maximum improvement as shown in Figure 3-4.

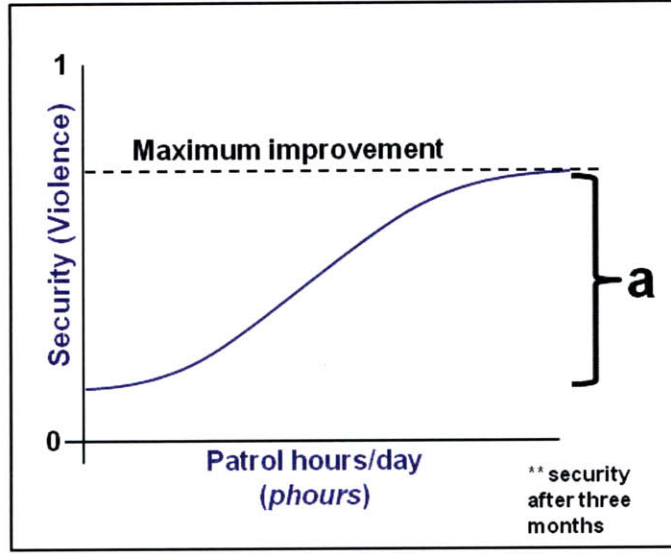


Figure 3-4: Security (Violence) vs. Patrol Hours per Day

Equation 3-18 defines sec^v .

$$sec^v_i = \frac{a_i}{\left[1 + be^{\left(-c \frac{f}{nodePop_i} \frac{pHours_i}{dutyDay} + d\right)}\right]} + (1 - violInitial_i) \quad (3-18)$$

The function's parameters are defined as follows:

- a_i – maximum improvement at each node that ranges from 0 to $(1 - violInitial_i)$. The default is $a_i = \frac{(violInitial_i)}{2}$ for all nodes. A_i can be chosen by the commander, presuming he can accurately predict violence reduction in each node.
- b, c, d – parameters for the logistic function that control rate of growth (actual values discussed in the next section).
- f – parameter that translates the “civilian to counterinsurgent ratio” for the logistics function (to be discussed in the next section).

Population determines the general shape of the curve for a node. The larger the population, the longer the curve stretches along the x-axis, and the more $pHours$ decrease violence. Figure 3-5 shows 3 nodes with the same initial violence but with different populations. The blue line has a population of 10,000 and extends out the furthest.

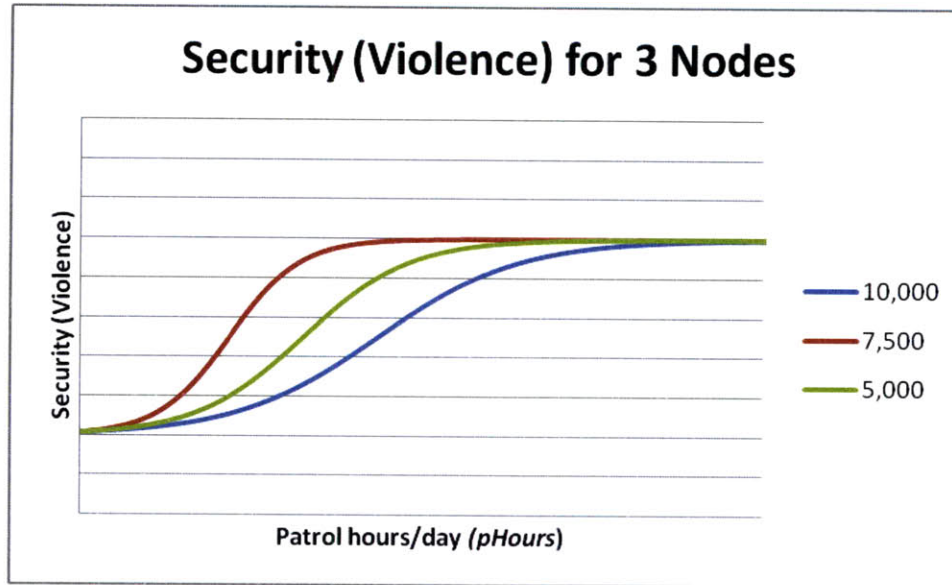


Figure 3-5: Security (Violence) for 3 Nodes with different Populations

It is important to note that the security function calculates the steady-state security at the end of a three month period. The algorithm assumes a consistent amount of daily patrolling over this period. Once the decision variables are determined, they do not change during the three months. This is not a dynamic model and does not include reaction by the insurgents to our patrolling or COP locations. Moreover, this model is independent of surrounding battalion areas of operation.

3.5.1.3 Calibrating the sec^v Function

In section 2, we introduced the notion that conducting successful counterinsurgency operations requires a minimum ratio of civilians to counterinsurgent. The parameters for sec^v were selected following this underlying concept. We equate “success” in counterinsurgency operations to achieving 80% of the maximum improvement in the sec^v function.

We calibrate sec^v so that $pHours = \frac{nodePop}{ccRatio} dutyDay$ corresponds to an 80% improvement of the maximum improvement, a .

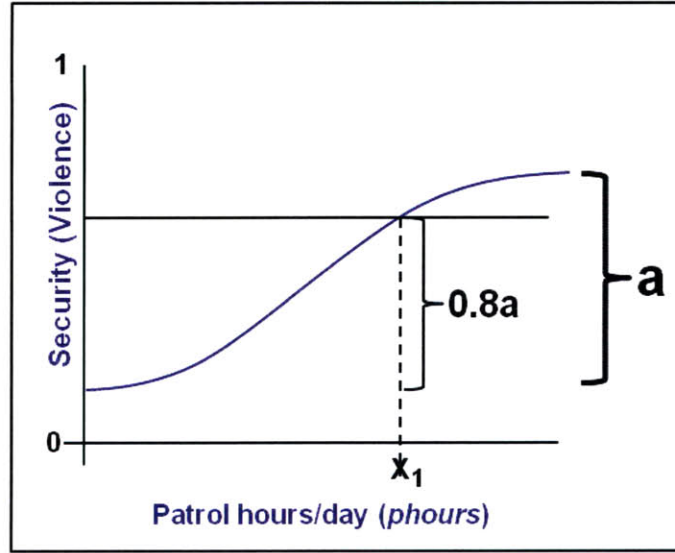


Figure 3-6: Security (Violence) Standardization

The value x_1 in Figure 3-6 is the point where $pHours = \frac{nodePop}{ccRatio} dutyDay$. The position on sec^v equals 80% of the maximum improvement. To follow this 80% rule, the function's parameters are set at $b = 7$; $c = 0.1$; and $d = 3.5$. For our default of 50:1 ratio of civilians to counterinsurgents, $f = 3500$.

As an example, at a duty day of 8 hours, a node with a population of 1000 would need 160 $pHours$ to secure the node: $\frac{1000}{50} 8 = 160$. The sec^v function is designed so that 160 $pHours$ corresponds to when the sec^v reaches 80% of maximum improvement ($0.8a$).

Equation 3-19 shows the sec^v equation with the functional parameters included:

$$sec^v_i = \frac{\frac{(violInitial_i)}{2}}{\left[1 + 7e^{\left(-0.1 \frac{3500}{nodePop_i} \frac{pHours_i}{dutyDay} + 3.65 \right)} \right]} + (1 - violInitial_i) \quad (3-19)$$

3.5.2 Security and Insurgent Activities

A node with minimal levels of violence or attacks may appear to be a secure area, but the presence and activities of insurgents produce an unsecure environment. Insurgent activities decrease the level of security for a number of reasons. In instances where the insurgents are co-opting the population, the people are endangered if they do not cooperate. Insurgents use intimidation and extortion to obtain supplies, shelter, and information. This intimidation deters the population from cooperating with security forces or supporting the government for a long

term solution. Moreover, the existence of insurgents illustrates the government's inability to police the area and perpetuates an environment of instability. Finally, the insurgents' presence greatly increases the possibility of a clash between US or host nation security forces, which could endanger the population and produce collateral damage.

3.5.2.1 Security versus Insurgent Activities

Three factors will reduce insurgent activities at a particular node: patrolling, emplacing a COP, and stationing the HHC. We arbitrarily allow each factor to reduce $\frac{1}{4}$, or 25%, of the insurgent activity. Operational, not all insurgent activities can be eradicated in a three-month period, so the most the model allows insurgent activities to be reduced is by 75%.

The sec^{insurg} is modeled as:

$$sec^{insurg}_i = A + B + C + (1 - insurgActInit_i) \quad (3-20)$$

Where:

$$A = \left(\frac{insurgActInit_i}{4} \right) \min \left[\frac{1}{\frac{dutyDay}{ccRatio} nodePop_i} pHours, 1 \right] \quad (3-21)$$

$$B = \left(\frac{insurgActInit_i}{4} \right) \min [0.02(x_i + cohq_i), 1] \quad (3-22)$$

$$C = \left(\frac{insurgActInit_i}{4} \right) 0.083hhc_i \quad (3-23)$$

The first term, **A**, represents the increase in sec^{insurg} due to patrolling. The slope depends on the parameters $nodePop$, $ccRatio$, and $dutyDay$. The maximum improvement due to patrolling is $\frac{insurgActInit_i}{4}$, or one quarter of the initial insurgent activity. We propose the first term for sec^{insurg} is linear with respect to additional patrol hours per day. As the number of patrol hour per day increases, the security gradually increases until insurgents find it difficult to operate freely or anonymously. Population security eventually plateaus because of the uncertainty in how long US or host nation forces will remain. The people are reluctant to believe their security situation has resolved for the long term.

The second term, **B**, expresses the improvement due to the potential presence and size of a COP. Unlike sec^v , the presence of a COP impacts the value of sec^{insurg} . The emplacement of a COP has a long-term effect on security as the local population witness American and host nation security forces sharing the dangers by living in their neighborhood. Independent of patrolling, the introduction of a COP raises the security because of the constant presence deters insurgent

activities. We assume that a COP with more soldiers would generate more patrols that travel through the node. Maximum improvement occurs when the total number of combat and company headquarter soldiers equals 50 soldiers ($x_i + cohq_i = 50$). We surmise that any COP with more than 50 soldiers has no additional impact on security. Again, the maximum improvement in security due to a COP is $\frac{insurgActInit_i}{4}$.

Term **C** models HHC's contribution. If the COP includes the HHC, local security will increase even further, due to the increase in vehicle and helicopter traffic associated with the headquarters. There is only one HHC per battalion and thus, only one node in the battalion area of operation can benefit from basing this unit. The node with the HHC will experience an increase in security of $\frac{insurgActInit_i}{4}$. A COP cannot base the HHC without combat soldiers; it must meet the constraint in Equation 3-8: if **B** = 0, then **C** = 0.

The last element of Equation 3-20, $(1 - insurgActInit_i)$, represents the initial security at the node.

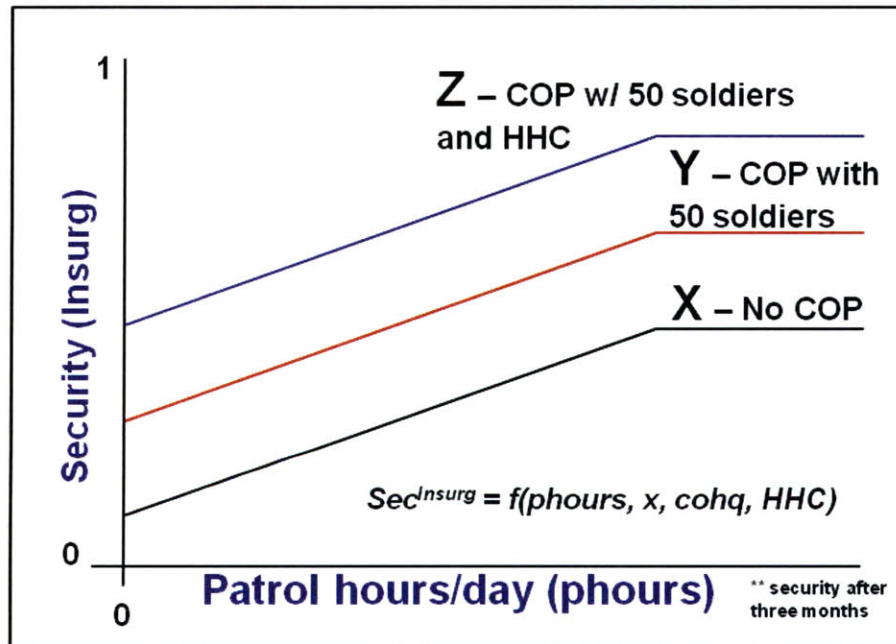


Figure 3-7: Example of Security (Insurgent) vs. Patrol Hours per Day

Figure 3-7 shows sec^{insurg} for 3 nodes with identical characteristics but with different COP configurations. All three functions have the same slope and reach their maximum at the same number of patrol hours per day. A node with a COP that has fewer than 50 soldiers would fall on a parallel line between **X** and **Y**.

Without a COP, sec^{insurg} can be increased by at most $\frac{insurgActInit_i}{4}$. A node with a COP of 50 soldiers, the HHC, and sufficient patrolling hours, sec^{insurg} is improved by $\frac{3}{4}insurgActInit_i$.

3.5.3 Security and Host Nation Force Effectiveness

The desired end state of a counterinsurgency is a functioning legitimate government and host nation forces that can provide security for the country. Improvements in the effectiveness of host nation forces will allow them to assume greater responsibility for security operations. The mere presence of host nation forces provides a measureable level of security. While US soldiers could occupy an area and reduce the violence to acceptable levels, the local population knows the Americans will eventually depart. Because of this, the people's security outlook is uncertain. If, however, it appears host nation forces are significantly contributing to security and the reduction in violence, the population has a greater sense of security for the long-term. This security is different than the reduction of violence. A more effective host nation force will gain the trust and confidence of the local population, because the host nation forces are viewed as being 'one of them.'

3.5.3.1 Improving Host Nation Force Effectiveness

The model assumes that, through combined patrolling, US soldiers can train and be role models for improving the effectiveness of host nation security forces. Additionally, the combined patrols ensure that the local population witnesses host nation security forces actively patrolling. We assume the ideal ratio of host nation agent to US soldiers is 3:1. This ratio is based on the experiences of deployed Army officers who were surveyed and interviewed for this research. A 3:1 ratio enables each US soldier to monitor a small group of host nation forces, but ensures the preponderance of the combined patrol is host nation soldiers. A small US presence reinforces the population's perception that the host nation security forces are leading the patrol. A larger US force would have the benefit of individual pairing and more personnel attention for each host nation agent but language barriers and limited number of interpreters would make a larger US contingent impractical. Host nation force effectiveness is measured on a continuous scale 0-1.

We represent the improvement of host nation force effectiveness as linearly related to additional US soldiers, but we limit the overall improvement. The maximum improvement depends on four parameters:

1. Number of host nation forces, hr^p
2. Population at a node, $nodePop$
3. Initial effectiveness of host nation forces, $effInitial$
4. Civilian to counterinsurgent ratio, $ccRatio$

The key parameters are $nodePop$ and hr^p . A small force, no matter how well trained and led, cannot adequately secure a large population.

Equation 3-26 shows the effectiveness, $effect$, for node i .

$$effect_i = (1 - effInitial_i) \frac{\min\left[(\sum_k x^p_{ki}), \left(\frac{hr^p_i}{3}\right)\right]}{\frac{nodePop_i}{ccRatio}} + effInitial_i \quad \forall i \quad (3-24)$$

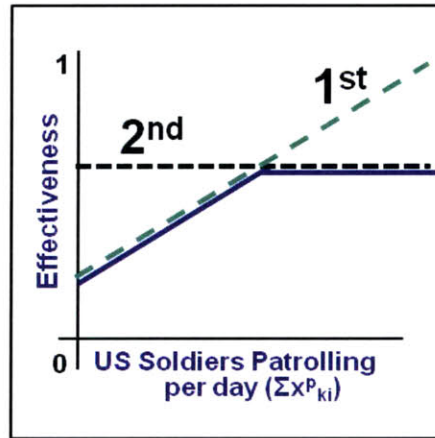


Figure 3-8: Host Nation Forces Effectiveness vs. U.S. Soldiers

An increasing number of US soldiers conducting daily combined patrols will shift the host nation forces closer to their effectiveness potential. The linear improvement corresponds to the 1st expression in the minimum of Equation 3-24 (represented in Figure 3-8 by green dashed line). As $\sum_{k=1}^K x^p_{ki}$ increases, the $effect$ increases at a rate that depends on the population of the node (section 3.4.4), the ratio of civilians to counterinsurgents (section 3.4.3), and the initial effectiveness (section 3.4.3). The 2nd expression in the minimum of Equation 3-24 is the maximum security, where an additional US soldier has no impact on improvement. This maximum (represented in Figure 3-8 by the black dashed line) is a constant based on the four parameters mentioned above and a ratio of 3 host nation forces to 1 US soldier. The number of

US soldiers at the point where the effectiveness reaches maximum improvement depends only on hn^p . The function for Equation 3-24 follows the path of the blue line in Figure 3-8: initially with a positive slope but reaches a point where the slope is zero.

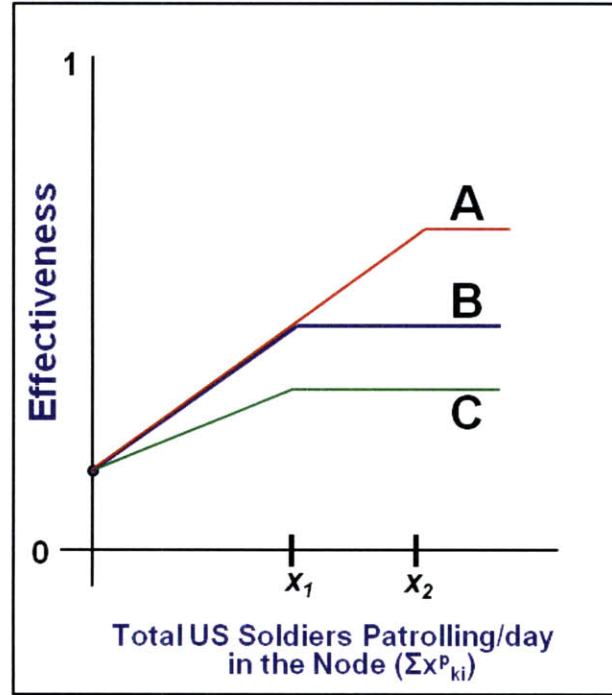


Figure 3-9: Example of Improvements to Host Nation effectiveness

Node Relationship
$effInitial_A = effInitial_B = effInitial_C$
$nodePop_C > nodePop_B = nodePop_A$
$hn^p_A > hn^p_B = hn^p_C$

Table 3-6: Nodal Relationship between Parameters

Figure 3-9 shows the effectiveness function for three nodes, A, B, and C. Table 3-6 shows the relationship between the parameters for the nodes in Figure 3-9.

The three nodes, A, B, & C, have the same $effInitial$. Node B, the blue line, and node A, the red line, have the same population, so the slope of improvement is the same for the two nodes. However, node A has a greater hn^p so the potential for effectiveness is higher and it requires more US soldiers, x_2 versus x_1 , to reach that maximum point.

Node C, the green line, and node B have the same hn^p , but with different populations. Node C has a larger population so it has a smaller slope and a lower potential for effectiveness. Because both nodes B and C have the same hn^p , the number of US soldiers patrolling to reach

the maximum, x_1 , is the same. In general, there is greater potential for improvement for a larger hn^p , a lower initial effectiveness, or a smaller population.

3.5.3.2 Security vs. Host Nation Force Effectiveness

Security from confidence in host nation forces, sec^{hn} , is measured on a continuous 0-1 scale.

$$Sec^{hn} = effect \quad (3-25)$$

Because of the equality relationship in Equation 3-25, sec^{hn} becomes a function of total US patrolling in the node as seen in Figure 3-10.

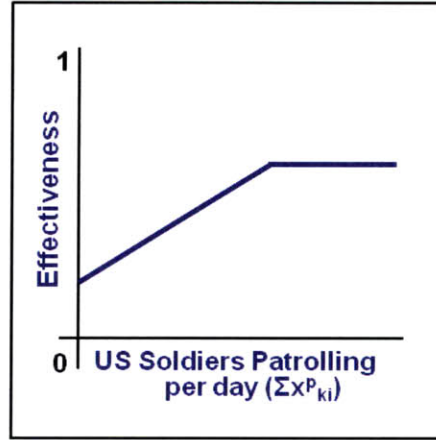


Figure 3-10: Security (Host Nation) vs. Soldiers Patrolling

Equation 3-26 calculates sec^{hn} directly as we combine Equation 3-24 and 3-25.

$$sec^{hn}_i = (1 - effInitial_i) \frac{\min\left[(\sum_k x^p_{ki}), \left(\frac{hn^p_i}{3}\right)\right]}{\frac{nodePop_i}{ccRatio}} + effInitial_i \quad \forall i \quad (3-26)$$

3.5.3.3 Determining Patrol Hours

The change of effectiveness of host nation forces, $effDelta$, (Equation 3-27) is used to compute patrol hours.

$$effDelta_i = effect_i - effInitial_i \quad \forall i \quad (3-27)$$

Patrol hours, $pHours$, consist primarily of the US soldiers' daily patrol hours, but it also includes the additional patrol hours due to improvement of host nation force effectiveness. We assume host nation security forces were already patrolling in the node so we do not include those patrol hours. However, we assume the improvement in effectiveness of host nation forces corresponds to additional patrolling.

$$pHours_i = \sum_{k=1}^K (g_{ik} x^p_{ki}) + dutyDay \, effDelta_i \, hn^p_i \quad \forall i \quad (3-28)$$

Equation 3-28 shows how $pHours$ for node i is computed. The first term determines the US soldiers' patrol hours. The contribution of each US soldier patrolling in node i depends on where that soldier is based. The number of soldiers from node k patrolling at node i is multiplied by the associated ground time, g_{ik} , for nodes i and k . All nodes in the area of operation are summed to determine the total US soldier contribution.

The second part of Equation 3-28 computes the contribution of improved host nation security forces. As stated previously, we assume the effectiveness of host nation force corresponds to amount of patrolling. An increase in effectiveness will translate to increased hours of patrolling for each host nation agent on patrol. When $dutyDay = 8$, an increase in effectiveness of 0.25 ($effDelta = 0.25$) will increase each host nation soldier's patrol hours by 2.

The model considers an ineffective host nation force, $effInitial = 0$, as not patrolling at all, while a host nation force with an $effInitial = 1$ is patrolling the equivalent of a full duty day, $dutyDay$.

3.6 The Problem Formulation

Below is the entire mathematical model. A master list of variables and parameters is found in Appendix B. The model is deterministic and a mixed-integer program containing a binary variable. The program is linear except for the sec^v term in the objective function which is non-linear and non-convex.

$$\max \sum_{i=1}^I w_i PopSec_i \quad (3-13)$$

$$PopSec_i = c_1 sec^v_i + c_2 sec^{insurg}_i + c_3 sec^{hn}_i \quad \forall i \quad (3-15)$$

$$sec^v_i = \frac{\frac{(violInitial_i)}{2}}{\left[1 + 7e^{\left(-0.1 \frac{3500}{nodePop_i} \frac{pHours_i}{dutyDay} + 3.65\right)}\right]} + (1 - violInitial_i) \quad \forall i \quad (3-19)$$

$$\begin{aligned} sec^{insurg}_i = & \left(\frac{insurgActInit_i}{4}\right) \min \left[\frac{1}{\frac{dutyDay}{ccRatio} nodePop_i} pHours, 1 \right] + \\ & \left(\frac{insurgActInit_i}{4}\right) \min [0.02(x_i + cohq_i), 1] + \\ & \left(\frac{insurgActInit_i}{4}\right) 0.083hhc_i + (1 - insurgActInit_i) \end{aligned} \quad \forall i \quad (3-20)$$

$$sec^{hn}_i = (1 - effInitial_i) \frac{\min[(\sum_k x^p_{ki}), (\frac{hn^p_i}{3})]}{\frac{nodePop_i}{ccRatio}} + effInitial_i \quad \forall i \quad (3-26)$$

Subject to:

$$\sum_{i=1}^I v_i \leq n \quad (3-4)$$

$$\sum_{i=1}^I hhc_i = 120 \quad (3-5)$$

$$\sum_{i=1}^I cohq_i = 60 \quad (3-6)$$

$$v_i \leq n y_i \quad \forall i \quad (3-7)$$

$$x_i \geq m y_i \quad \forall i \quad (3-8)$$

$$x^f_i \geq forPro_i y_i \quad \forall i \quad (3-10)$$

$$x_i = x^f_i + \sum_{k=1}^K x^p_{ik} \quad \forall i \quad (3-1)$$

$$supp_i = hhc_i + cohq_i \quad \forall i \quad (3-2)$$

$$v_i = x_i + supp_i \quad \forall i \quad (3-3)$$

$$pHours_i = \sum_{k=1}^K (g_{ik} x^p_{ki}) + dutyDay effDelta_i hn^p_i \quad \forall i \quad (3-28)$$

$$x^f_i \geq 0, \text{ integer} \quad \forall i \quad (3-29)$$

$$x^p_{ik} \geq 0, \text{ integer} \quad \forall i, k \quad (3-30)$$

$$y_i \in \{0, 1\} \quad \forall i \quad (3-31)$$

$$hhc_i \in \{0, 120\} \quad \forall i \quad (3-32)$$

$$cohq_i \in \{0, 15\} \quad \forall i \quad (3-33)$$

3.7 Solving the Mathematical Model

Although a number of non-linear solution methods could be used on this problem, the integer constraints complicate many of these methods. Fortunately, the monotonically increasing nature of sec^v , along with its symmetry around a central point, makes it suitable for linear

approximation. Employing linear approximation, we can solve the mathematical model using a mixed-integer linear program (MILP).

3.7.1 Piecewise Linear Approximation of Security (Violence)

Given the non-convex, non-linear behavior of sec^v , we transform it by conducting piecewise linear approximation using binary variables [31].

The function is segmented into short linear pieces that closely approximate the original function. Two “elbows” are chosen as initial break points for the function. The third derivative, set to zero, determines the elbow points (x_1 & x_2) along the x-axis. Additionally, we have the initial point (x_0), as well as a fourth point where the function is extremely close to its maximum. By symmetry, this last segment is the same length as our first segment ($x_3 - x_2 = x_1 - x_0$) \Rightarrow ($x_3 = x_2 + x_1$) where ($x_0 = 0$). Figure 3-11 shows the location of x_0 , x_1 , x_2 , and x_3 on an example.

We can expand the linear approximation to closely represent the curve by adding four additional break points:

$$x_4 = 0.75 x_1 \quad (3-34)$$

$$x_5 = 0.25 (x_2 - x_1) + x_1 \quad (3-35)$$

$$x_6 = 0.75 (x_2 - x_1) + x_1 \quad (3-36)$$

$$x_7 = 0.25 x_1 + x_2 \quad (3-37)$$

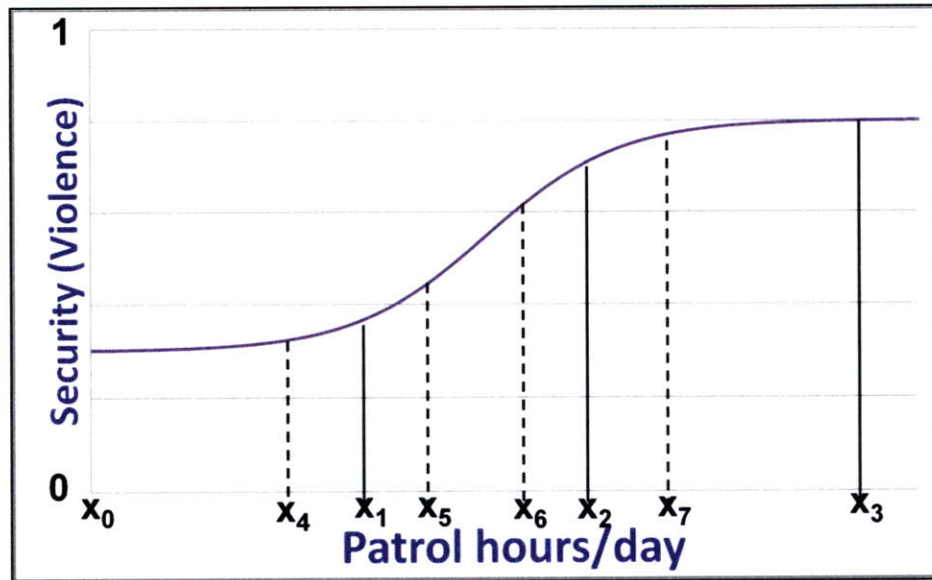


Figure 3-11: Break Points

The continuous piecewise linear approximation is shown in Figure 3-12. This linear approximation consists of 8 break-points ($x_0 - x_7$) and seven segments (A-G). The segments, A and G, are equal in length and slope. Each pair, B-F and C-E, also share the same segment length and slope. Segment D is unique and has the greatest slope.

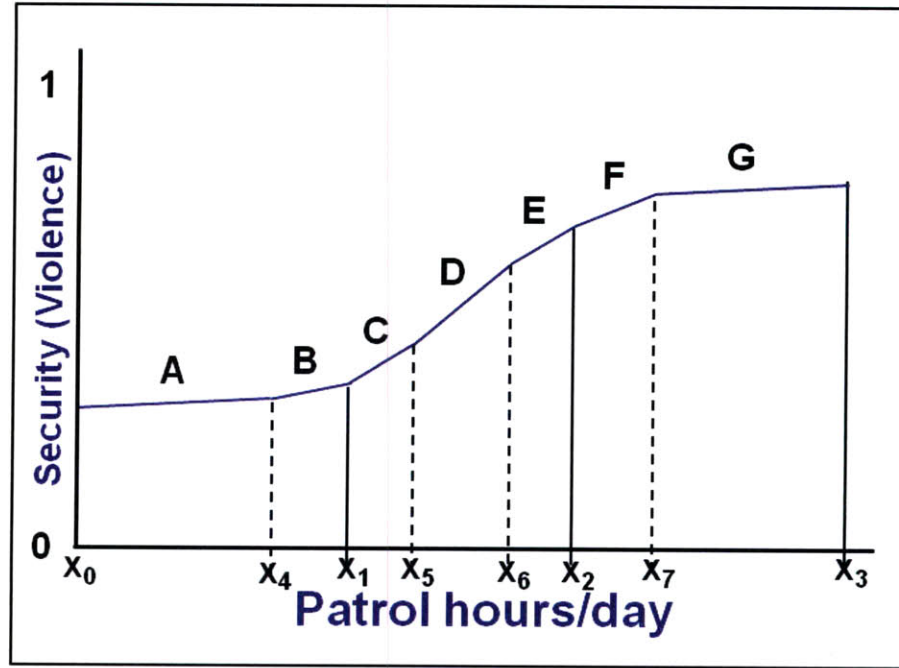


Figure 3-12: Piecewise Linear Approximation

For modeling this piecewise linear function using binary variables, we need the set of $(x_i, sec^v(x_i))$ at the break points. We substitute x_i values into the original equation to calculate the $sec^v(x_i)$ value at each break point. With the $(x_i, sec^v(x_i))$ pairs, we introduce a binary variable to complete the linear piecewise formulation.

3.7.2 MILP Solution

We used two sets of software to solve our problem: MATLAB 7.6.0 from MathWorks, Inc. and ILOG OPL IDE with the CPLEX 11.1 solver. We used MATLAB for our data input and to preprocess the ground time matrix, \mathbf{G} , and the piecewise linear approximation set points. We export all pertinent parameter data to ILOG OPL where CPLEX solves the MILP algorithm using a solution polishing heuristic on the branch and cut method. The solver finds an initial feasible solution using conventional branch and cut. ILOG CPLEX then searches for better solutions by examining the other branches of the original problem. In CPLEX, the difference between the best integer objective and the objective functions of the remaining sub problems can

be set as a parameter called “the absolute tolerance on the gap.” When the difference falls below the value of this absolute tolerance, the mixed integer optimization stops and a solution is provided.

The flow of information of the model is shown in Figure 3-13.

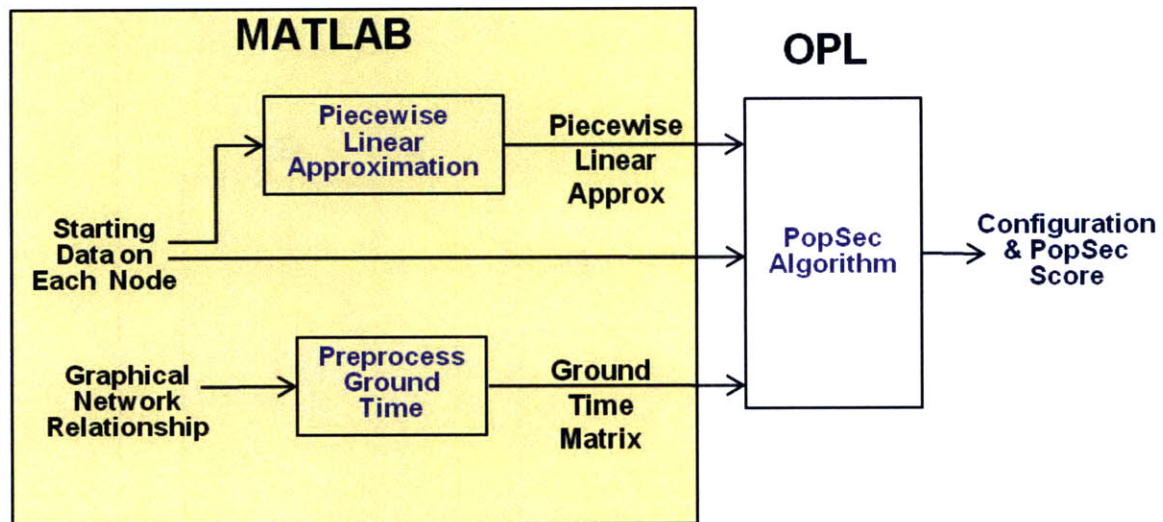


Figure 3-13: Software Configuration

4 RESULTS & ANALYSIS

To test and evaluate our model and to analyze the operational problem, we desire scenarios similar to current and anticipated insurgent environments. Insurgencies usually occur in a failed or failing state. Iraq, Afghanistan, and Lebanon are clear examples of recent insurgencies. Unfortunately, most of the military's pertinent data from Iraq or Afghanistan is classified; instead, we use representative data similar to the situation in Iraq in 2004-2007 or Afghanistan in 2006-2010. We created two baseline scenarios that varied by population size, dispersion of nodes, but with similar initial conditions. Both scenarios' locations are representative of terrain found in southwestern Asia.

- Scenario 1: Krasnovia – 110 kilometers by 80 kilometers with a large population
- Scenario 2: Cortina – 50 kilometers by 80 kilometers in a rural and desolate environment

From exploring the solution space with these two scenarios, we present analyses about the properties of the population security function. We conduct further analyses to test the validity of some of our operational assumptions and the sensitivity of the model to changes in parameters and constraints. Finally, we test the computational demands of the model.

4.1 Krasnovia Scenario

The name Krasnovia comes from a fictional country used by the Army in war games since the 1980s. The area of operation used in the model has mountainous terrain on the borders with a high plain in the middle.

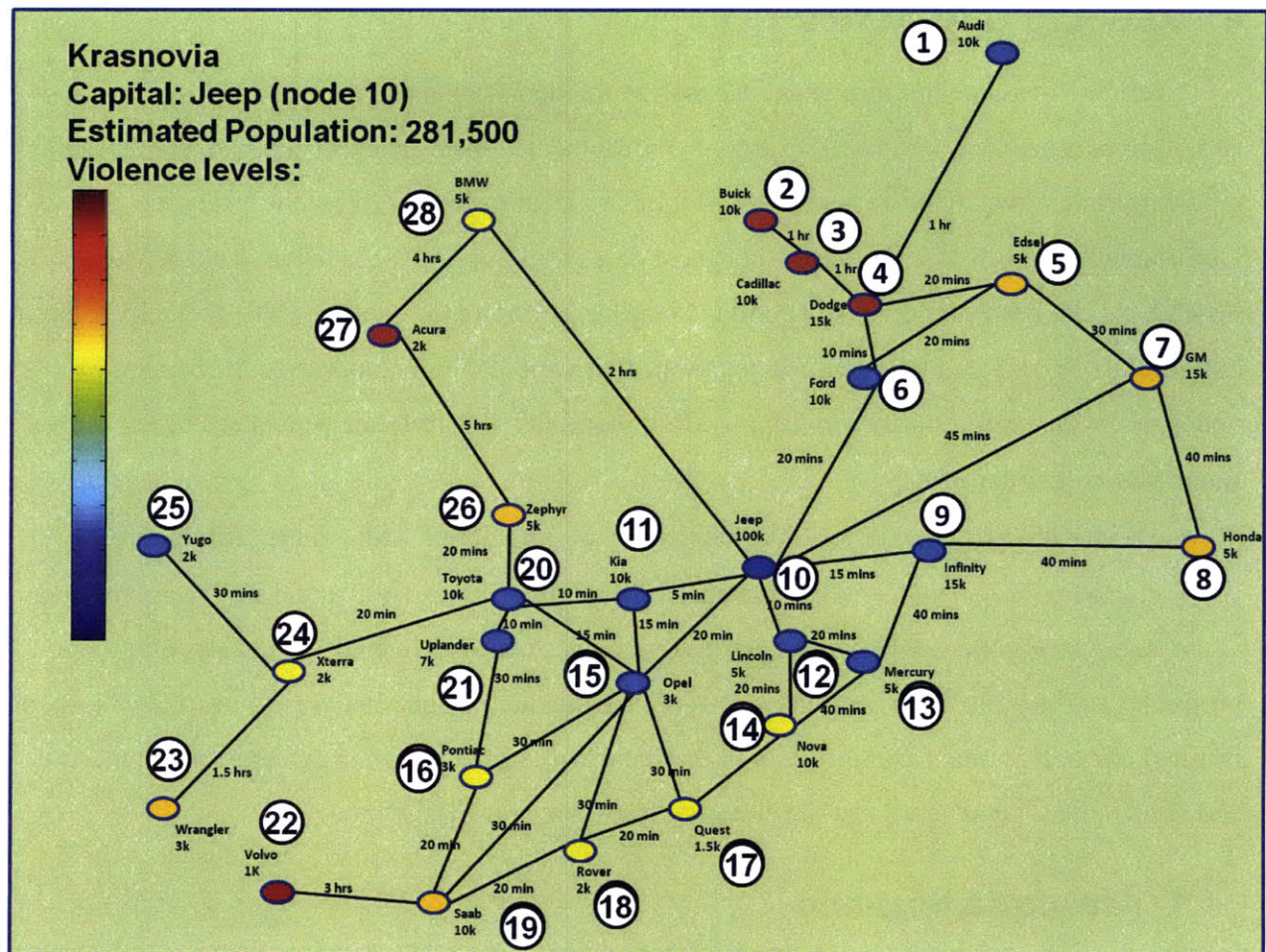


Figure 4-1: Krasnovia

Figure 4-1 shows the 28 nodes of Krasnovia where each is numbered and named after an automobile or automobile manufacturer. The area measures roughly 110 kilometers across by 80 kilometers. The capital, Jeep (node 10), is a densely populated city with 100,000 citizens. The other nodes are towns or consolidated villages that vary in population from 1,000 – 15,000. The total population for all the nodes is 281,500. The colored ovals represent the initial violence level in the node with red being the most violent and dark blue being the least violent. While the capital of Jeep and vicinity is relatively calm, Krasnovia has some hostile areas in the mountainous regions on the periphery.

Figure 4-1 also shows the arcs and their associated travel times between nodes. The arcs near the capital have short travel times due to improved roads. The arcs away from the capital represent poor roads in mountainous regions, so they have long travel times.

For the remaining attributes of each node, we sample from distributions representative of conditions similar to the situation in Iraq in 2004-2007 or Afghanistan 2006-2010:

- Host nation forces on patrol: hr^p – Each node has a 0.5 probability of containing host nation forces. For nodes that contain host nation forces, we sample from the absolute value of a normal distribution with a mean of 20 and a variance of 64, $hr^p \sim |N(\mu = 20, \sigma^2 = 64)|$.
- Initial effectiveness of host nation forces: $effInitial$ – If a node does not have host nation forces ($hr^p = 0$), then $effInitial = 0$. For nodes that contain host nation forces, $effInitial \sim |N(0.2, 0.04)|$. The absolute value of the normal ensures all values are positive, but it allows some of the nodes to have moderate effectiveness. With the absolute value, the mean is approximately 0.25.
- Initial level of insurgent activity: $insurgActInit$ $\sim |N(0.3, 0.0625)|$. The absolute values ensure all values are positive.
- Initial level of attacks: $attacks$ – The nodal values are sampled from a continuous uniform distribution $\sim U(0, 1)$.
- Quality of the COP: $copQual$ – The nodal values are a discrete uniform distribution

$$p_{copQual}(k) = \begin{cases} 0.333, & \text{if } k = 1, 2, 3 \\ 0, & \text{otherwise} \end{cases}$$

4.2 Cortina Scenario

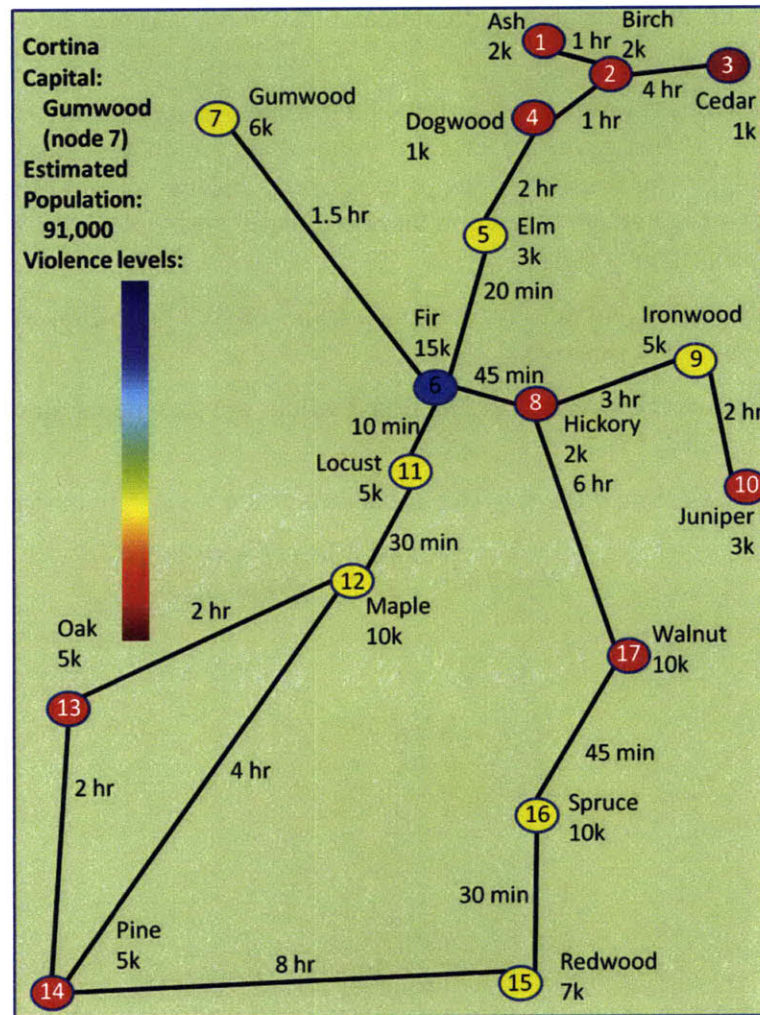


Figure 4-2: Cortina

Figure 4-2 shows the area of operation for Cortina. The name Cortina also comes from a fictional country used by the Army in war games. Cortina represents a country with more mountainous terrain than Krasnovia, but less geographic area, fewer nodes, and less total population. The land mass is about 50 kilometers by 80 kilometers. Cortina has 17 nodes (named after trees) with a total population of 91,000. The largest node is 15,000 while the smallest is 1,000. Cortina contains rural terrain and limited passable roads, which increases travel time between most nodes. While Cortina has significant violence throughout the area, the nodal parameters (hr^p , $effInitial$, $insurgActInit$, $attacks$, and $copQual$) are taken from the same distributions as those of Krasnovia.

4.3 Visualization of Results

The PopSec score (Equation 3-13) is scalar, takes on values in the closed interval $[0-1]$, and represents the security of the entire area of operation.

We refer to the solution and individual values for security functions as “the Configuration:”

1. COP locations
2. Forces based at each COP
3. Patrol schema: lists which nodes each patrol is originating from
4. sec^v , sec^{insurg} , and sec^{hn} , for each node

Analyzing the Configuration enables us to better understand the algorithm and, if necessary, make mathematical adjustments.

A map of the network helps in visualizing the Configuration. An output from the model is a graphical depiction of the area of operation showing which nodes have COPs, the relative size of the force based at each, and the number of soldiers patrolling at each. We use the Configuration map to examine and compare COP placements and patrol recommendations. The map gives us an abbreviated Configuration but does not portray the following: exact number of soldiers at each node, where support soldiers are based, and from which nodes the soldiers are patrolling. For this information, we have to look at the whole Configuration.

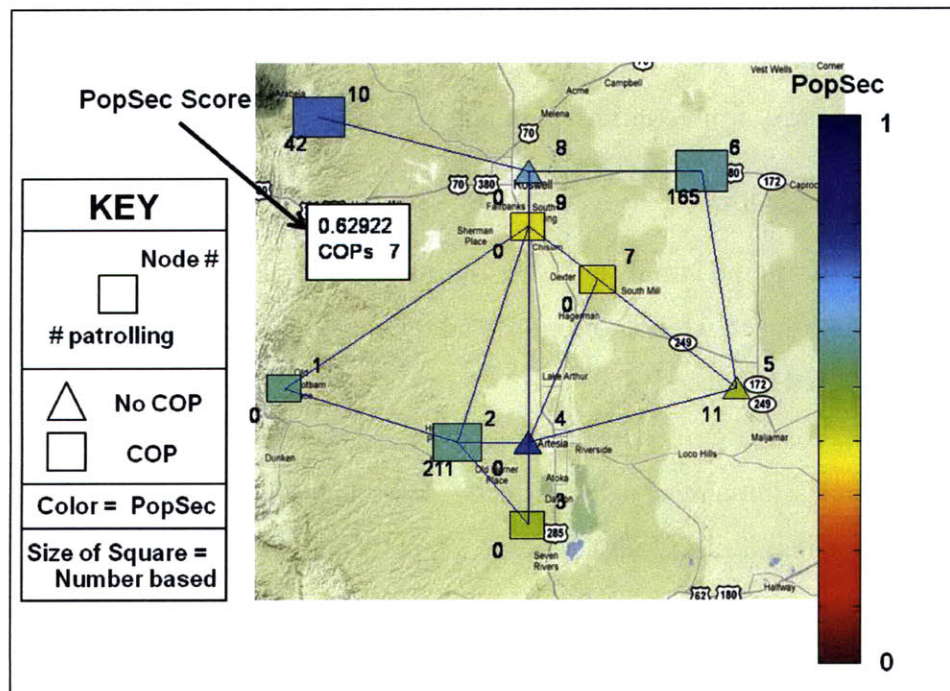


Figure 4-3: Example of Output overlaying the Map

Figure 4-3 is a Configuration map of the 10 node example introduced in section 1.2.1 (Figure 1-1 and Figure 3-1). A node displayed as a square has a COP, while a triangle indicates a node without a COP. The size of the square indicates the number of soldiers based at the COP. The node number is listed above and to the right of the geometric shape. Of the ten nodes in Figure 4-3, seven have COPs and the COP at node 6 is the largest. The map explicitly indicates how many soldiers are patrolling in each node to the lower left of the shape. Node 2 has the most soldiers patrolling – 211 soldiers. Node 3, at the bottom of the map, has a COP, but no soldiers patrolling. In that instance, the soldiers not on guard from node 3 are allocated to patrol in other node(s). In section 4.4.4, we will discuss why nodes like 1, 3, 7, and 9, have a COP and no soldiers patrolling. The color inside the shape indicates the node's PopSec score. The map output also includes the PopSec score on the left side.

4.4 Baseline Results and Analysis

A full strength infantry battalion is utilized for each scenario. The commander's top priority in improving population security is violence reduction, followed by reducing insurgent activity, and improving host nation force effectiveness.

We set the commander's security weights, c_j , as follows:

- $c_1 = 0.5$ -- Security by reducing violence: sec^v
- $c_2 = 0.3$ -- Security by reducing insurgent activities: sec^{insurg}
- $c_3 = 0.2$ -- Security from confidence in host nation forces: sec^{hn}

4.4.1 Krasnovia Baseline

Table 4-1 below shows the initial conditions for the Krasnovia scenario. We kept the node weights at their default level, which is proportional to the population. Recall that all initial conditions are measured between 0 and 1.

For this scenario, host nation forces patrol 12 of the 28 nodes, ranging in force size from 7 to 34 host nation soldiers. Initial host nation effectiveness ranges from 0.01 to 0.35. The insurgency activity is highest in Wrangler (node 23) at 0.66 and lowest in Buick (node 2) at 0.05. As seen on the scenario map in Figure 4-4, the violence is high in nodes 2, 3, 4, and 22.

Node	Name	Population	Initial Insurgent Activity	Host Nation Forces	Initial Host Nation Effect	Initial Violence	Node Weight	Initial PopSec
1	Audi	10,000	0.40	8	0.09	0.2	0.036	0.60
2	Buick	10,000	0.05	25	0.03	0.8	0.036	0.39
3	Cadillac	10,000	0.30	0	0.00	0.8	0.036	0.31
4	Dodge	15,000	0.29	26	0.05	0.8	0.053	0.32
5	Edsel	5,000	0.30	27	0.01	0.6	0.018	0.41
6	Ford	10,000	0.22	26	0.35	0.2	0.036	0.70
7	GM	15,000	0.57	0	0.00	0.6	0.053	0.33
8	Honda	5,000	0.17	0	0.00	0.5	0.018	0.50
9	Infinity	15,000	0.41	0	0.00	0.2	0.053	0.58
10	Jeep	100,000	0.52	0	0.00	0.1	0.355	0.59
11	Kia	10,000	0.48	0	0.00	0.2	0.036	0.56
12	Lincoln	5,000	0.44	0	0.00	0.2	0.018	0.57
13	Mercury	5,000	0.31	7	0.07	0.2	0.018	0.62
14	Nova	10,000	0.47	0	0.00	0.4	0.036	0.46
15	Opel	3,000	0.44	12	0.14	0.2	0.011	0.59
16	Pontiac	3,000	0.24	31	0.13	0.4	0.011	0.56
17	Quest	1,500	0.21	0	0.00	0.5	0.005	0.49
18	Rover	2,000	0.23	24	0.13	0.4	0.007	0.56
19	Saab	10,000	0.07	0	0.00	0.7	0.036	0.43
20	Toyota	7,000	0.24	0	0.00	0.2	0.025	0.63
21	Uplander	10,000	0.33	0	0.00	0.2	0.036	0.60
22	Volvo	1,000	0.38	20	0.01	0.9	0.003	0.24
23	Wrangler	3,000	0.66	0	0.00	0.6	0.011	0.30
24	Xterra	2,000	0.21	0	0.00	0.4	0.007	0.54
25	Yugo	2,000	0.46	24	0.05	0.2	0.007	0.57
26	Zephyr	5,000	0.50	34	0.15	0.6	0.018	0.38
27	Acura	2,000	0.54	0	0.00	0.2	0.007	0.54
28	BMW	5,000	0.05	0	0.00	0.4	0.018	0.58

Table 4-1: Krasnovia – Initial Conditions

The last column of Table 4-1 also shows the nodes' initial PopSec score prior to introducing US soldiers to the area. The lowest level of population security is at node 22, which is the most violent node. The other nodes with low initial PopSec scores are 3, 4, 7, and 23. Figure 4-4 shows the visual depiction of the initial PopSec scores for the scenario. The blue triangles are nodes with high PopSec scores. The red are the lowest scores. A majority of the nodes are in the middle ranges and green colored.

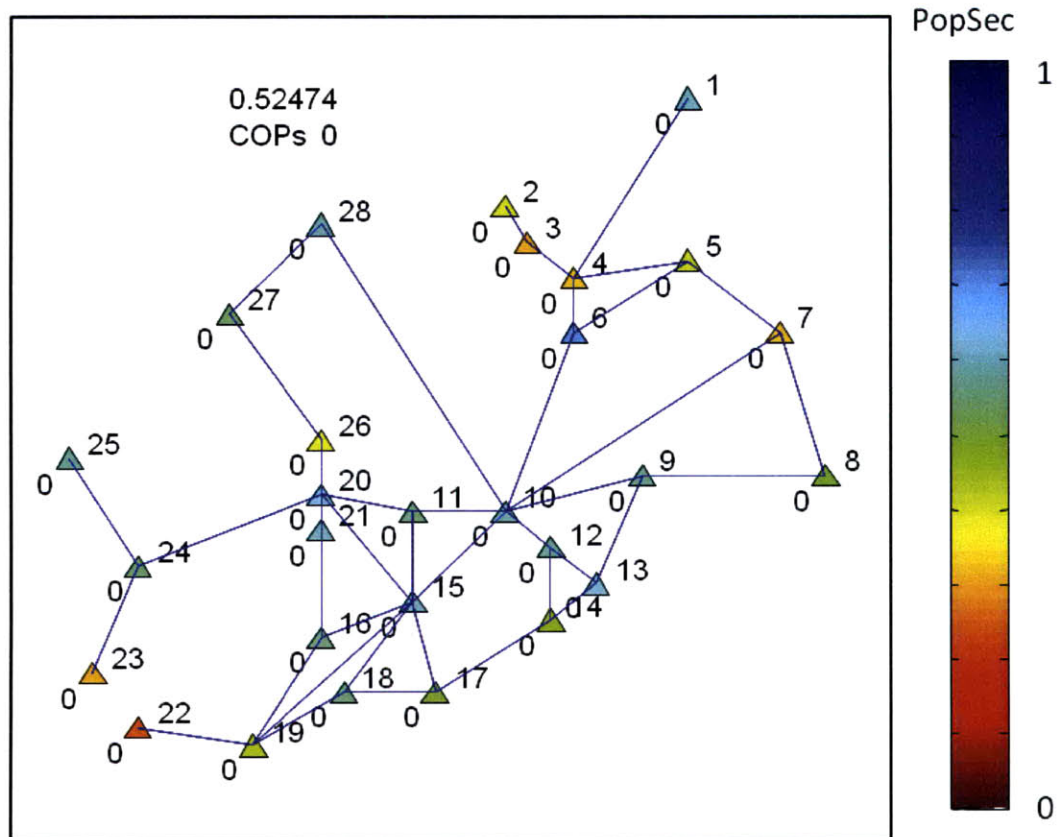


Figure 4-4: Krasnovia – Initial PopSec Scores

Figure 4-5 shows the Configuration map for the maximization of PopSec for Krasnovia, and shows where COPs should be emplaced and where soldiers should patrol. Comparing the node colors in Figure 4-5 and 4-4 shows the improvements in population security. For instance, node 4, in the right center, is originally orange, but is seen in Figure 4-5 as light green. Node 7, in the left center, went from yellow to a blue-green.

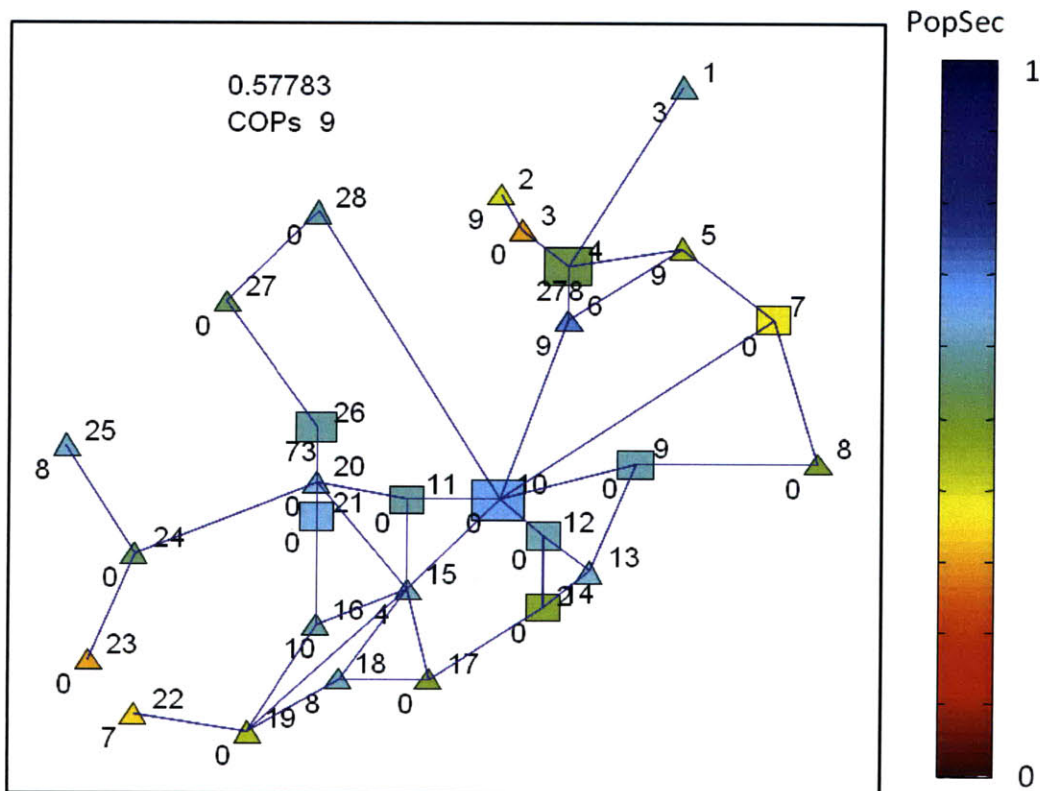


Figure 4-5: Krasnovia – Map Configuration

The solution recommends 9 COPs and soldiers to patrol in 12 of the nodes. One node, Dodge (node 4), is allocated a large COP and a very large number of patrol hours. Examining the original attributes of the nodes, we can see why this node receives so many resources. Dodge has the second highest population of 15,000 and has a very high level of violence (0.8). Given the commander's priority to reduce violence, it became imperative to patrol there.

Table 4-2 shows the breakdown of where the soldiers are based and their roles. The headquarters and headquarters company (HHC) is established in Jeep (node 10), which is the largest node in population. Recall that the node with the HHC gets a $\frac{1}{4}$ reduction in insurgent activity. Jeep's high node weight, in conjunction with a relatively high initial insurgent activity, produces the greatest improvement of PopSec score for the HHC. Company headquarters are established in nodes 7, 9, 14, and 21, primarily because of high insurgent activities in these nodes. Insurgent activity is the only element of population security that support soldiers can impact.

Node	Name	US Combat Soldiers	Force Protection	Support Soldiers	Total Soldiers	Population	Initial Insurgent Activity	Initial Violence
4	Dodge	141	15	0	141	15,000	0.29	0.8
7	GM	35	12	15	50	15,000	0.57	0.6
9	Infinity	35	9	15	50	15,000	0.41	0.2
10	Jeep	50	12	120	170	100,000	0.52	0.1
11	Kia	50	9	0	50	10,000	0.48	0.2
12	Lincoln	44	6	0	44	5,000	0.44	0.2
14	Nova	35	9	15	50	10,000	0.47	0.4
21	Uplander	35	6	15	50	10,000	0.33	0.2
26	Zephyr	85	12	0	85	5,000	0.50	0.6

Table 4-2: Krasnovia – Nodes with COPs

There are a variety of patrols throughout the area of operation. Table 4-3 shows where daily patrols are sent to.

Node	Name	Soldiers on patrol per day	phours	Host Nation Forces	Initial Host Nation Effect	Population
1	Audi	3	11.28	8	0.09	10,000
2	Buick	9	26.11	25	0.03	10,000
4	Dodge	278	2036.53	26	0.05	15,000
5	Edsel	9	65.71	27	0.01	5,000
6	Ford	9	58.35	26	0.35	10,000
13	Mercury	2	14.38	7	0.07	5,000
15	Opel	4	31.52	12	0.14	10,000
16	Pontiac	10	105.81	31	0.13	3,000
18	Rover	8	81.52	24	0.13	2,000
22	Volvo	7	61.19	20	0.01	1,000
25	Yugo	8	68.51	24	0.05	2,000
26	Zephyr	73	610.24	34	0.15	5,000

Table 4-3: Krasnovia – Nodes with Patrolling

The nodes with soldiers patrolling matched exactly the nodes containing host nation forces. The striking result is the small size of patrols to the nodes (from 2-10 soldiers). This is best explained by the small host nation force at each node; recall that host nation force effectiveness is maximized at a ratio of 3 host nation to 1 US soldier. Upon inspection, 10 of the 12 nodes (all but nodes 4 and 26) allocate the exact number of soldiers to maximize sec^{hn} . The moderate patrol presence in Zephyr (node 26) will be discussed shortly and in a follow-on section (4.3.4).

The small patrol sizes generated by the algorithm were initially disconcerting. In reality, an operational patrol would not depart with less than 12 soldiers, and probably averaged about 15

soldiers. The intent of this model is to assist in COP planning while considering patrolling. We wanted to account for patrolling but not to overly constrain the model. Although we did not specify minimum patrol size, we can modify our assumption of *pHours* to account for this deviation from reality. We originally stated that *pHours* are the daily number of patrol hours consistently executed. If we instead define it as the **average** number of patrol hours per day, the model still functions as formulated but incorporates the operational consideration. In such an instance, instead of node 15 being patrolled everyday by 4 soldiers, it could be patrolled every third day by 12 soldiers, resulting in the same number of *pHours* and the same reduction in violence.

Figure 4-6 shows the initial and final population security.

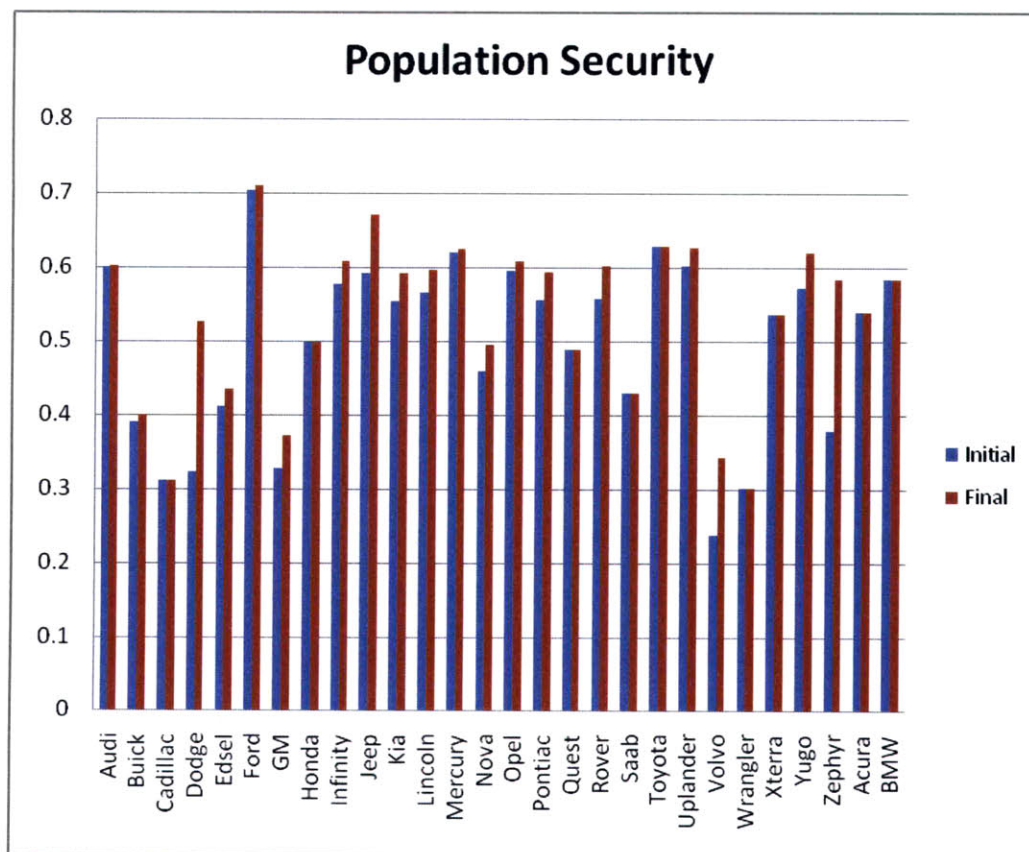


Figure 4-6: Krasnovia – PopSec (Initial vs. Final)

It shows a large increase in Dodge and Zephyr. While Dodge took a large COP and many soldiers to improve, Zephyr was less resource intensive for similar amounts of PopSec improvement. By emplacing a medium-size COP and moderately patrolling, Zephyr increases its PopSec score by 54% as seen in Figure 4-7. Zephyr has the combination of the largest

number of host nation forces, a relatively high insurgent activity, and a moderate level of violence. Because of these factors, it was selected as a COP location and to receive patrols.

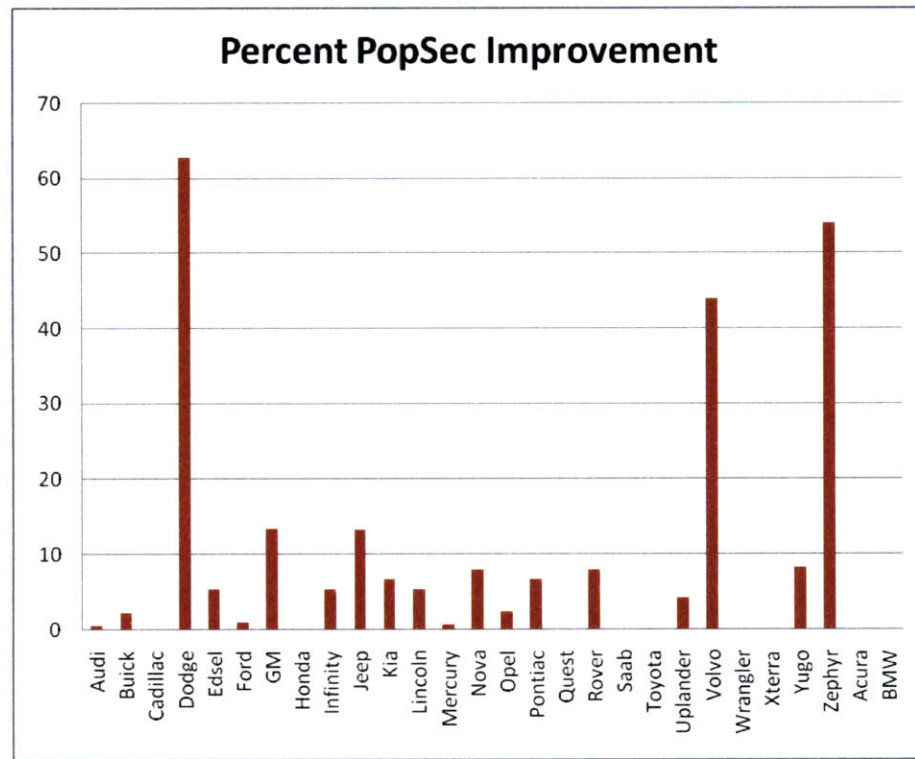


Figure 4-7: Krasnovia – Percent PopSec Improvement

A number of less secure nodes receive no resources. Cadillac (nodes 3) and Wrangler (node 23) obtain no resources but are the second and third lowest initial PopSec, respectively. Wrangler has a small population, and thus a small nodal weight. With a small nodal weight, it is not a good candidate for security forces because it provides little improvement to the overall PopSec score. Cadillac is just the opposite. It probably has too large of a population and requires too many resources to realize marginal PopSec improvements. This concept of weighted scores will be addressed further in section 4.4.4.

We solve the formulation (ref Section 3.6) for this scenario using a Dell Optiplex 740 desktop with AMD Athlon 64 X2 Dual Core Processor 5600+ 2.91 Ghz and 2.00 GB of RAM. Using the CPLEX MILP absolute tolerance gap of 0.00160, it takes 25.267 seconds to solve by examining over 10,610 sub problems. An absolute tolerance gap smaller than 0.00160 does not converge. It is important to note that this tolerance gap works for these specific parameters in the Krasnovia scenario. Using a different set of random values for the parameters, the same tolerance gap may make the algorithm converge much quicker or not at all.

4.4.2 Cortina Baseline

Cortina is much smaller in population and size than Krasnovia, but has more unimproved roads that make travel times longer. The long travel times make it challenging to patrol in remote nodes without COPs. The commander still wants to reduce the violence so all security weights remained unchanged.

- $c_1 = 0.5$ -- Security by reducing violence: sec^v
- $c_2 = 0.3$ -- Security by reducing insurgent activities: sec^{insurg}
- $c_3 = 0.2$ -- Security from confidence in host nation forces: sec^{hn}

Node	Name	Population	Initial Insurgent Activity	Host Nation Forces	Initial Host Nation Effect	Initial Violence	Node Weight	Initial PopSec
1	Ash	2,000	0.40	8	0.02	0.8	0.022	0.29
2	Birch	2,000	0.05	25	0.03	0.8	0.022	0.39
3	Cedar	1,000	0.30	0	0.00	1	0.011	0.21
4	Dogwood	1,000	0.29	26	0.05	0.8	0.011	0.32
5	Elm	3,000	0.30	27	0.01	0.6	0.033	0.41
6	Fir	15,000	0.22	26	0.39	0.1	0.163	0.76
7	Gum	6,000	0.57	0	0.00	0.4	0.065	0.43
8	Hickory	2,000	0.17	0	0.00	0.8	0.022	0.35
9	Ironwood	5,000	0.41	0	0.00	0.6	0.054	0.38
10	Juniper	3,000	0.52	0	0.00	0.8	0.033	0.24
11	Locust	5,000	0.48	0	0.00	0.4	0.054	0.46
12	Maple	10,000	0.44	0	0.00	0.5	0.109	0.42
13	Oak	5,000	0.31	7	0.02	0.8	0.054	0.31
14	Pine	5,000	0.47	0	0.00	0.8	0.054	0.26
15	Redwood	7,000	0.44	12	0.10	0.4	0.076	0.49
16	Spruce	10,000	0.24	31	0.11	0.5	0.109	0.50
17	Walnut	10,000	0.21	0	0.00	0.8	0.109	0.34

Table 4-4: Cortina – Initial Conditions

The initial conditions shown in Table 4-4 are very similar to the Krasnovia scenario. We used the same sample distributions, so *insurgActInit* and host nation forces match the first 17 nodes of Krasnovia. *effInitial* values are different since their computation includes the node's population. In this scenario, Gum (node 7) and Juniper (node 10) have the greatest insurgent activity. Eight of the 17 nodes have host nation forces ranging in size from 7 to 31 soldiers. The high initial violence results in nodal PopSec scores that are lower compared to Krasnovia. For Cortina, there are four nodes with an initial PopSec score under 0.30. Figure 4-8 shows the visual depiction of initial PopSec scores. The overall PopSec score for the area of operation is only 0.45169 which is 0.073 less than Krasnovia.

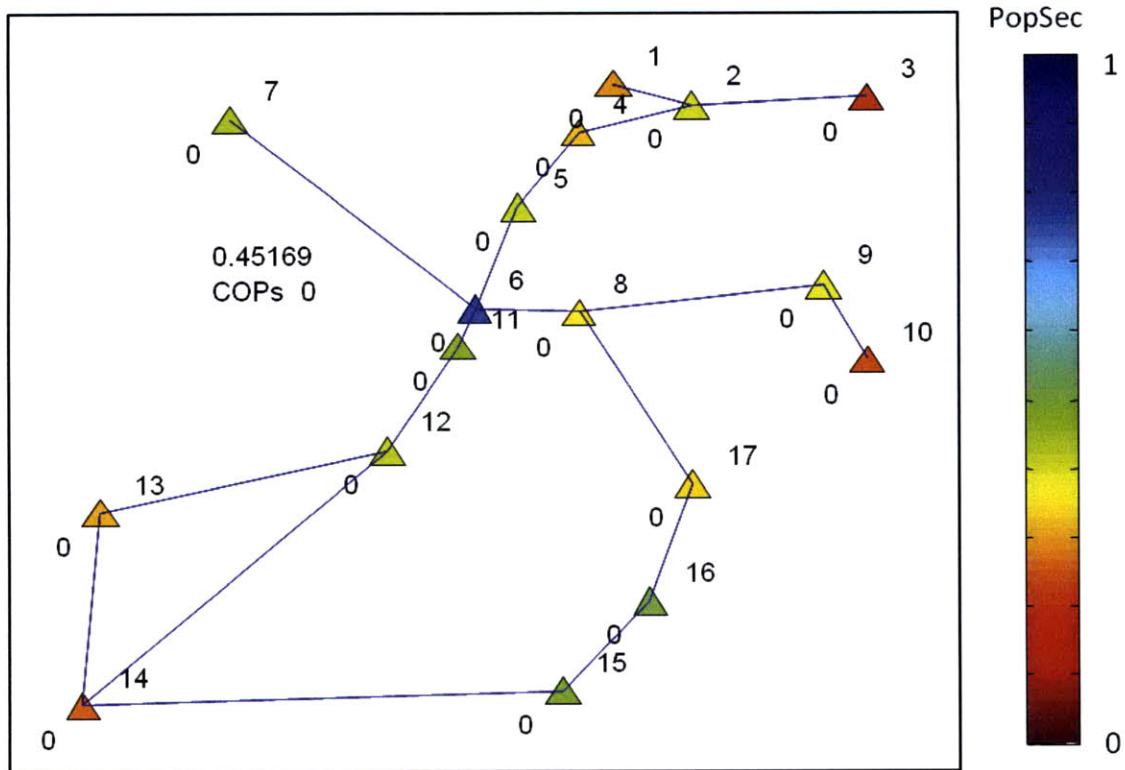


Figure 4-8: Cortina – Initial PopSec Scores

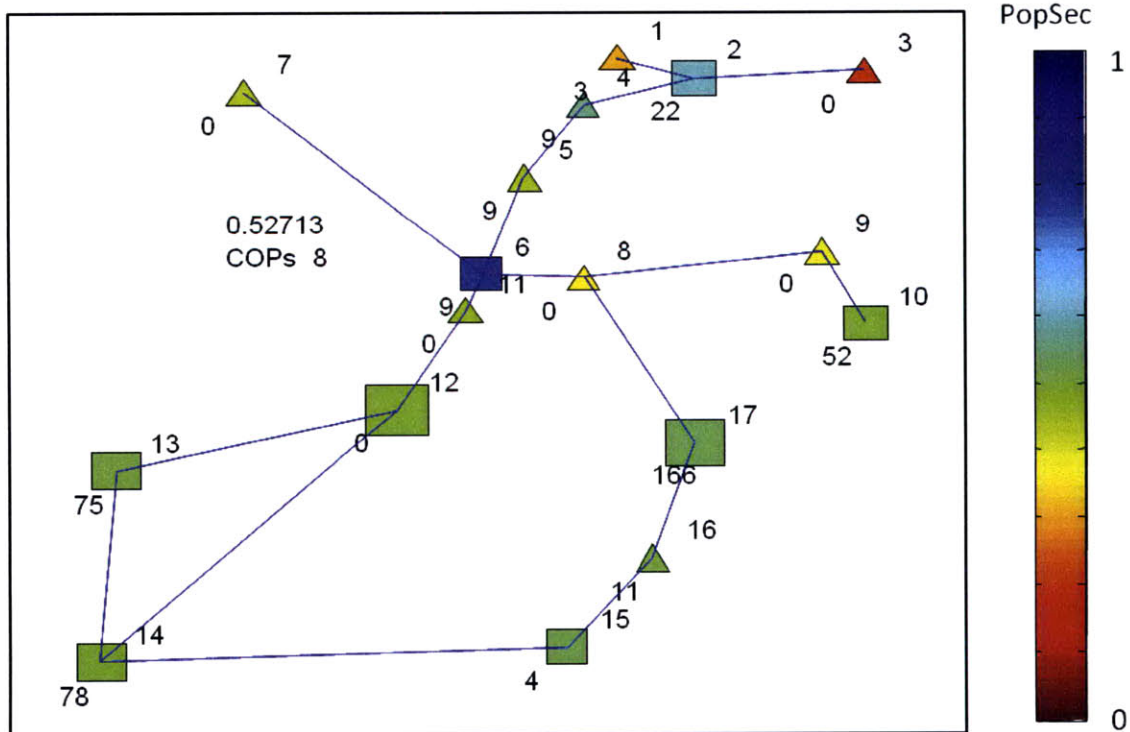


Figure 4-9: Cortina – Map Configuration

Figure 4-9 visualizes the solution for Cortina. The algorithm recommends 8 COPs and schedules patrols for 11 of 17 nodes. Table 4-5 gives the exact number of soldiers based at each node. The HHC was established at Maple (node 12) which, unlike Krasnovia, is not the largest node in population. Again, the node with the HHC gets a $\frac{1}{4}$ reduction in insurgent activity. Although Maple is $\frac{2}{3}$ as populated as the largest node, Fir (node 6), Maple has twice as much insurgent activity, so the emplacement of the HHC provides more overall population security improvement. The company headquarters are placed at nodes 6, 12, and 15, primarily because of high insurgent activities. The company headquarters located at node 2 appears to be an anomaly because of its low initial insurgent activity. Based on our constraints, the company headquarter had to be positioned at a node that already has a COP. PopSec improvement for a company headquarters depends upon these factors: support soldiers only improve sec^{insurg} , a total of 50 soldiers reach maximum improvement in sec^{insurg} , and only 1 company headquarter is allowed per node. The only node with less than 50 total soldiers that did not already have a company headquarters was node 2.

Node	Name	US Combat Soldiers	Force Protection	Support Soldiers	Total Soldiers	Population	Initial Insurgent Activity	Initial Violence
2	Birch	40	6	15	55	2,000	0.05	0.8
6	Fir	35	6	15	50	15,000	0.22	0.1
10	Juniper	58	6	0	58	3,000	0.52	0.8
12	Maple	35	15	135	170	10,000	0.44	0.5
13	Oak	87	12	0	87	5,000	0.31	0.8
14	Pine	87	9	0	87	5,000	0.47	0.8
15	Redwood	26	9	15	41	7,000	0.44	0.4
17	Walnut	142	9	0	142	10,000	0.21	0.8

Table 4-5: Cortina – Nodes with COPs

Table 4-6 shows the number of soldiers on patrol at each node. 5 out of 12 nodes have patrols of over 20 soldiers.

Node	Name	Soldiers on Patrol	<i>phours</i>	Host Nation Forces	Population	Host Nation Effect	Initial Violence
1	Ash	3	22.17	8	2,000	0.02	0.8
2	Birch	22	216.56	25	2,000	0.03	0.8
4	Dogwood	9	139.49	26	1,000	0.05	0.8
5	Elm	9	86.02	27	3,000	0.01	0.6
6	Fir	9	63.64	26	15,000	0.39	0.1
10	Juniper	52	416.00	0	3,000	0.00	0.8
13	Oak	75	601.29	7	5,000	0.02	0.8
14	Pine	78	624.00	0	5,000	0.00	0.8
15	Redwood	4	34.46	12	7,000	0.10	0.4
16	Spruce	11	88.39	31	10,000	0.11	0.5
17	Walnut	166	1269.70	0	10,000	0.00	0.8

Table 4-6: Cortina – Nodes with Patrolling

Walnut (node 17) is the highest in violence and second highest in population, and it became the main effort for patrols. Oak (node 13) and Pine (node 14) follow with the same level of violence but with half the population as Walnut. Juniper (node 10) is even smaller, yet with the same initial level of violence. Birch (node 2) and Ash (node 1) have the same population, but Birch receives more patrolling combat soldiers. Due to Birch having a larger contingency of host nation security forces, the US soldiers on patrol could both reduce violence and improve the effectiveness of the host nation forces; this contributes more to the total PopSec.

An apparent inconsistency in this scenario is Cedar (node 3) with a 1.0 in initial violence and the lowest initial PopSec score, but receives none of the security resources. Considering Cedar's small population and lack of host nation forces, it produces less population security than the other nodes and is not selected.

Figure 4-10 shows the population security at its initial and final level. A number of nodes experience significant PopSec improvements. Five nodes have an improvement of over 0.2 and six nodes had over a 50% improvement in PopSec as seen in Figure 4-11.

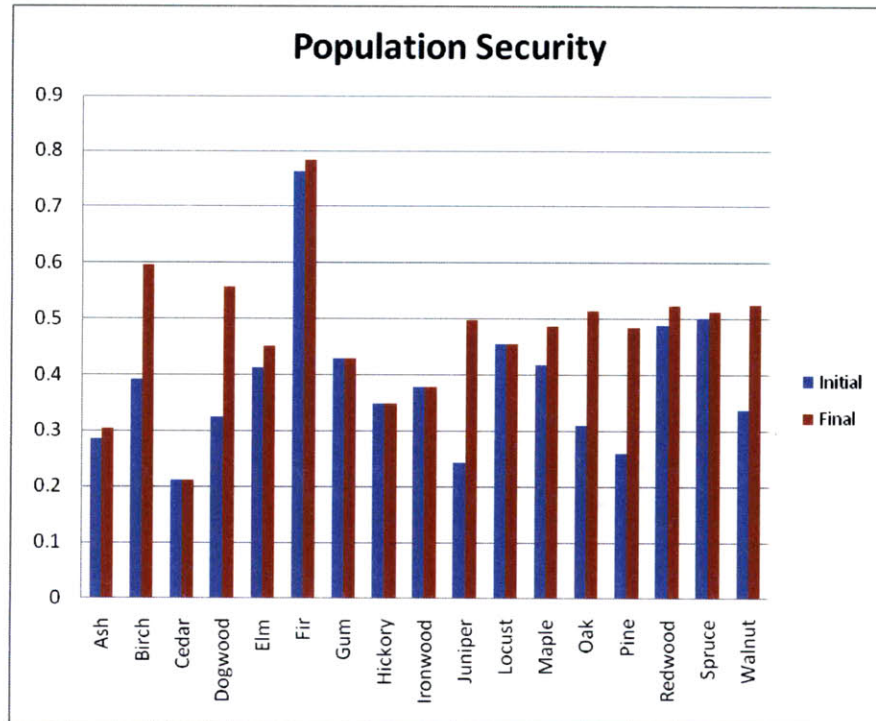


Figure 4-10: Cortina – PopSec (Initial vs. Final)

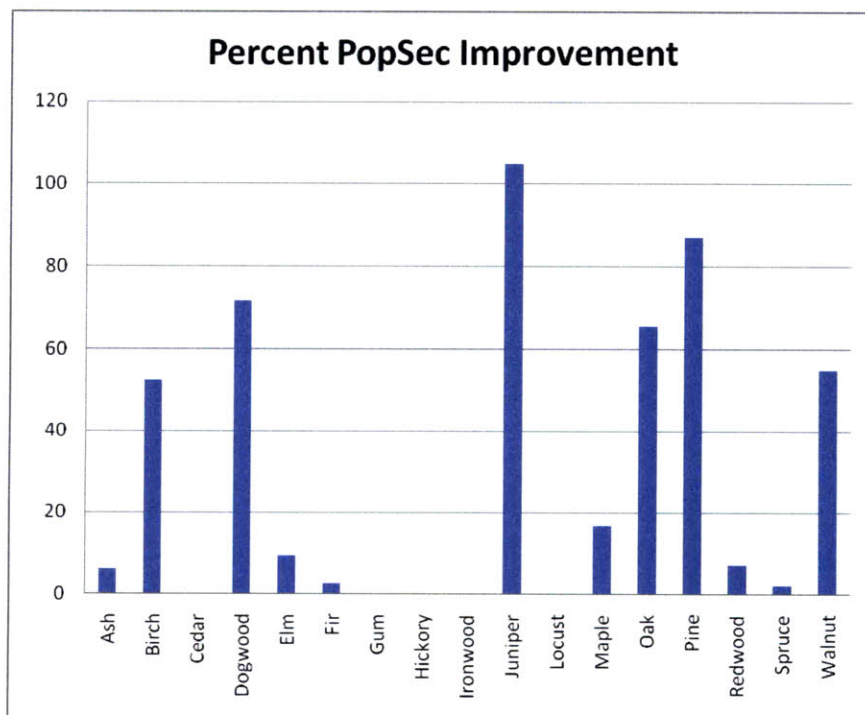


Figure 4-11: Cortina – Percent PopSec Improvement

Using the same computer system as Krasnovia, Cortina solves in 16.8125 seconds using an absolute gap tolerance of 0.00120. The solver checks over 18,100 sub problems.

4.4.3 Comparison of Scenarios' Results

The two scenarios show some noteworthy comparisons. Many of the relationships between the two results have obvious explanations, while others require more in-depth analysis. The scenarios differ in four main aspects as shown in Table 4-7:

	Krasnovia	Cortina
Population	281,500	91,000
Number of nodes	28	17
Average travel time between nodes	45 min	2 hours
Average initial level of violence	0.42	0.64

Table 4-7: Comparison of Krasnovia and Cortina

Cortina has a greater increase in PopSec score and significant PopSec improvement in more nodes than Krasnovia. The smaller population makes securing the populace in Cortina more achievable. Overall, fewer resources are required to reduce the high level of violence in Cortina's smaller nodes. Krasnovia has one large node that took over half of the combat soldiers to secure. We will discuss in section 4.4.4 the reason that so many soldiers were dedicated to just one node.

Although the scenarios differed in population, they have a similar number of COPs and nodes receiving patrols, but this happens for different reasons. Cortina has long travel times which make spreading out forces in numerous COPs crucial for patrols to have sufficient ground time. The 9 COPs in Krasnovia achieve a balance of decreasing insurgent activities without sacrificing too many soldiers to force protection.

The patrolling in Krasnovia only coincides with nodes containing host nation forces. We conjecture if an additional node in Krasnovia had host nation forces, that node would also be patrolled. For such a little investment, soldiers improving host nation force effectiveness have the greatest improvement of population security. US soldiers in Cortina patrol in all nodes with host nation forces but also operate extensively in violent nodes without host nation forces. The next section will explain this occurrence.

The solving time for both scenarios was relatively short, but results show disparity in the number of sub problems tested. Krasnovia solves in 25.267 seconds and examines 10,610 sub

problems, while it takes Cortina shorter, 16.8125 seconds, to examine 18,100 sub problems. The algorithm can examine different combinations for Cortina quicker because it has fewer nodes.

4.4.4 Analysis of Population Security Functions

Some results in our baseline runs are intriguing, such as:

- Allocating many soldiers to patrol in one node
- No patrols in nodes with high violence
- Different unit sizes change which nodes are patrolled

To explain these results, we need to look at the three security functions in further detail. We first examine them separately to understand each function's unique behavior and then together.

4.4.4.1 Security (Violence) Function

Recall that the security function for violence is non-linear and non-convex. Although we conducted linear approximation, the non-convexity of the piecewise linear function creates some unintuitive results. To examine sec^v independent of the other two elements of security, we set c_1 , the commander's weight for violence reduction, to 1.0 and $c_2 = c_3$ to 0.0, so PopSec score becomes a function of only sec^v_i . We want to examine the sec^v functions multiplied by the node weights, $w_i sec^v_i$.

As a simplified illustration, we explore six nodes from the example scenario (figures 1-1, 3-1, 3-2 and 4-3) with the characteristics shown in Table 4-8.

Node	Population	Initial Violence
3	10,000	0.7
4	15,000	0.2
5	5,000	0.8
6	10,000	0.9
7	15,000	0.8
10	2,000	0.5

Table 4-8: Node Information from Example Scenario

Three inputs are important to understanding $w_i sec^v_i$'s behavior: node weight, population, and maximum increase in security, a . The parameter a is set at one half of the initial violence and the node weights remain proportional to population.

As discussed in section 3.7.1, sec^v function is converted to a piecewise linear function by determining break points. A node with a small population has shorter distance between break-points, because it takes fewer patrols hours to secure the population and thus ascends more quickly compared to the larger nodes. When we graph the $w_i sec^v_i$ function, we see a node improves population security at an increasing rate because the slope initially increases at each break-point. The center segment of the piecewise linear function has the greatest rate of security increase before diminishing returns begin on the second half of the function. The maximum height of a $w_i sec^v_i$ curve depends on maximum improvement, a , and nodal weight, w .

Figure 4-12 shows the $w_i sec^v_i$ functions of the six nodes versus patrol hours per day. Each curve has the piecewise linear shape discussed in section 3.7.1. Node 10 has the smallest population and is the smallest curve in the graph. Given its small population, the line segments are short and it quickly reaches its maximum.

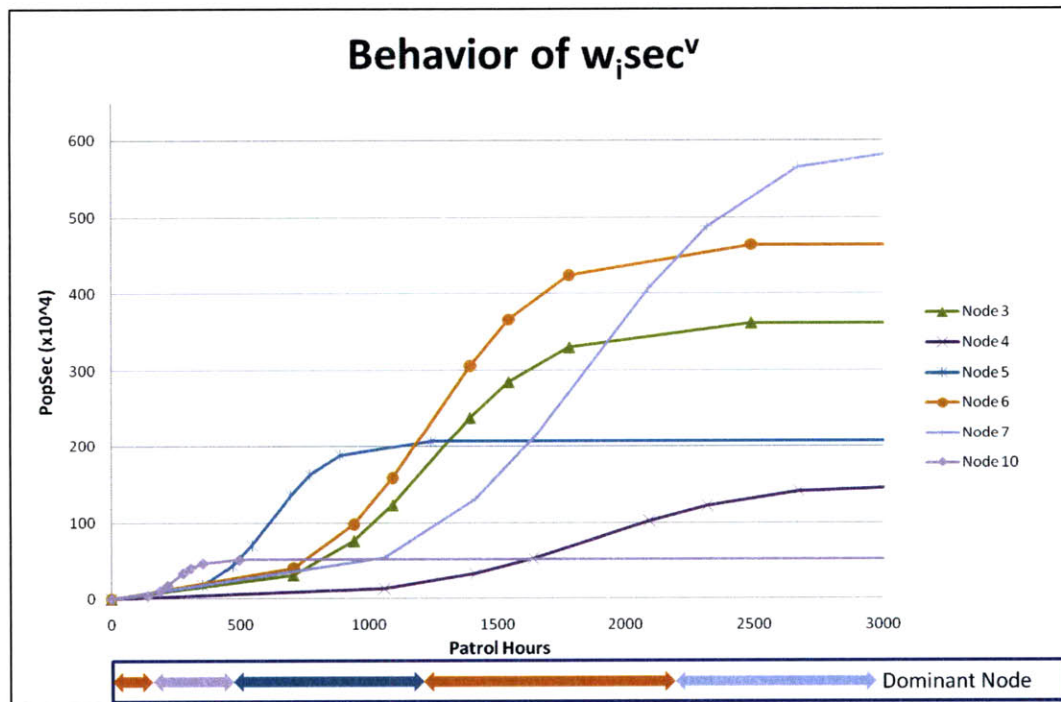


Figure 4-12: $w_i sec^v_i$ Functions for Selected Nodes

Figure 4-12 shows where individual nodes dominate other nodes as patrol hours increase. The dominant node provides the greatest improvement in PopSec at a particular value of $pHours$. By inspection, node 10 is most desirable when 200 to 500 $pHours$ are available (below 200 patrol hours will be covered at the end of this section).

If more than 500 patrol hours were available (greater than what achieves node 10's maximum), the algorithm would select node 5 instead, as it dominates the other nodes. At approximately 1200 *pHours*, node 6 dominates, and at approximately 2200 *pHours*, node 7 dominates. The bar at the bottom of figure 4-12 indicates the region where each node dominates.

Figure 4-12 only shows the individual nodes. We also want to examine the combination of two smaller nodes that could potential dominate a single large node. The combining of two nodes splits the patrol hours almost equally between each node. The splitting of patrol hours at certain ranges allow the most influential part of each function to contribute before diminishing returns.

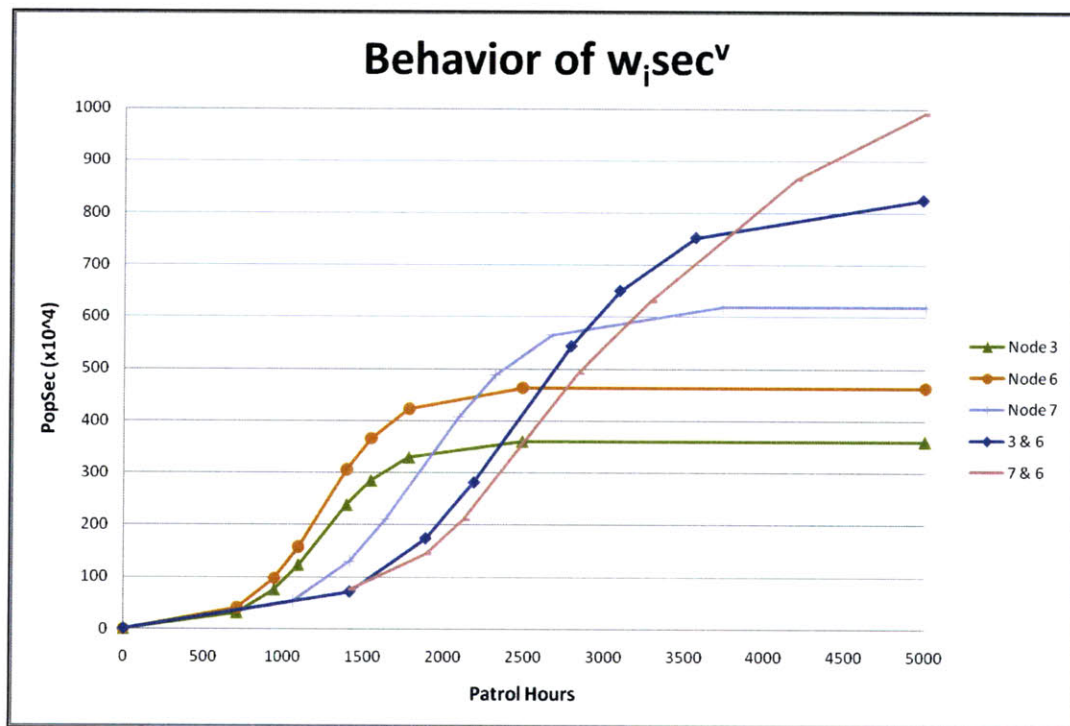


Figure 4-13: $w_i \text{sec}^v$ Functions with Node Combination

Figure 4-13 shows nodes 3, 6, and 7, and combination of node pairs (3 and 6) & (7 and 6). The combination of node 3 and 6 surpasses node 7 at approximately 2800. At this point, the algorithm will split the patrol hours fairly evenly between node 3 and 6. This coincides with where the slope is the highest for node 3 and node 6 individually (at 1400). The allocation to two nodes produces a greater improvement in population security than node 7 alone, for the same number of patrol hours. Eventually, a combination of node 6 and 7 surpasses that, at around 3,700 hours.

Given a large number of patrol hours, the algorithm will allocate patrol hours to the node (or nodes) providing the most improvement until it reaches its maximum. The algorithm will then allocate patrol hours to subsequent nodes or pairs in a similar manner. For a scenario with over 10,000 *pHours* available, the algorithm would maximize nodes 6 and 7 together, then node 3, and then node 5, etc. In the Cortina scenario, this process occurs when the four heavily-populated, violent nodes are allocated patrol hours.

When there are not enough *pHours* to reach the maximum of the next best node or pair, the algorithm devotes the *pHours* to the dominant node at the remaining number of patrol hours. In our example above, if after maximizing population security for node 7, only 300 *pHours* remains, and patrol hours are allocated to node 10. A similar instance occurs in the Krasnovia scenario: after the improvement of a violent, heavily-populated node, the algorithm selects a small node at the same level of violence because it was dominant for the remaining *pHours*.

Figure 4-14 the functions, $w_i sec^v_i$, near the origin. With a very small number of available patrol hours, less than 200, the greatest population security would occur at node 6.

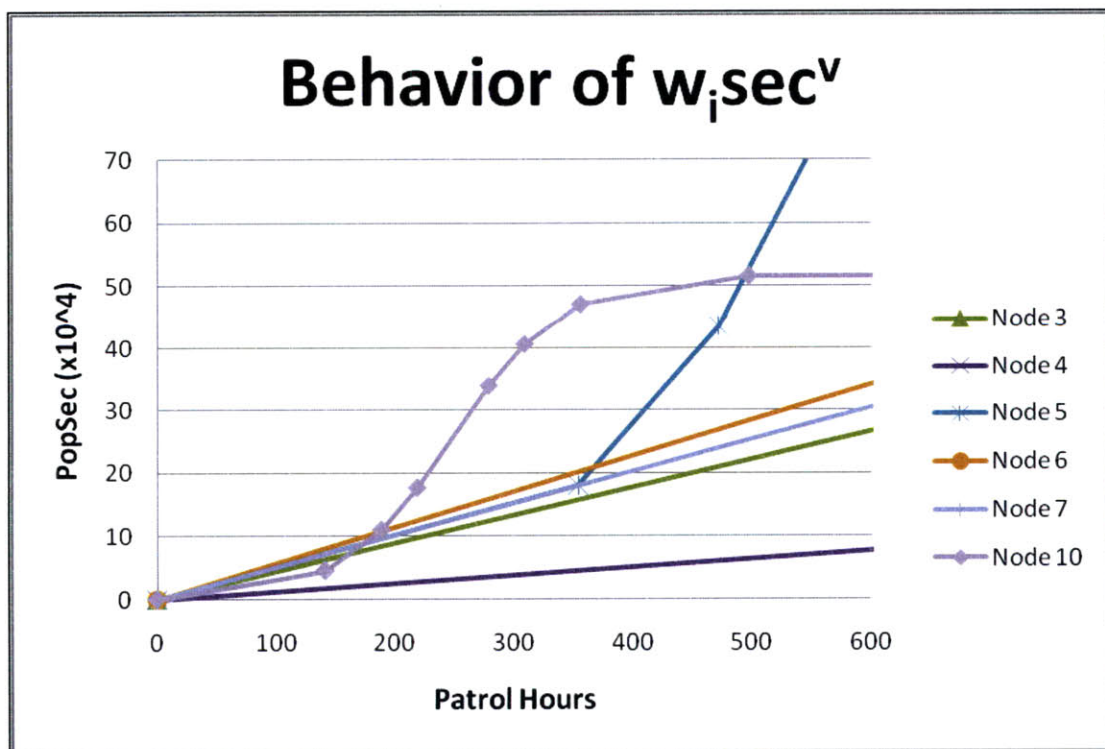


Figure 4-14: $w_i sec^v_i$ Functions near the Origin

4.4.4.2 Security (Host Nation) Functions

The linearity of sec^{hn} makes its behavior more predictable but it exhibits a few surprises. We already addressed the phenomenon of small US patrols. Because of the 3:1 ratio (host nation forces to U.S. soldier) to maximize host nation force effectiveness, only a few US soldiers were patrolling at those node . Both scenarios have small number of host nation forces which are typical for the early stages of Iraq and Afghanistan.

We want to analyze which individual node is more effective at improving the host nation force effectiveness and explain why. Again, we set $c_3 = 1$, so PopSec only includes improvement of host nation force effectiveness. Table 4-9 is data from the example scenario. Examining the data illustrates the difficulty in determining by inspection which node is best:

Node	Population	Host Nation Forces	Host Nation Effect
1	10000	34	0.09
4	15000	42	0.24
6	10000	32	0.17
9	5000	70	0.41
10	2000	63	0.41

Table 4-9: Node Information from the Example Scenario

The sec^{hn} function includes population, number of host nation forces on patrol, and their initial effectiveness. The value of sec^{hn} function, multiplied by the node weights, determine which node is the dominant. Although node 9 has the most host nation forces, it also has the most effective force and a smaller population. Node 1 has the lowest effectiveness but also fewer host nation forces. Node 4 has the largest population and a moderate host nation force size and effectiveness. Which of these nodes dominates?

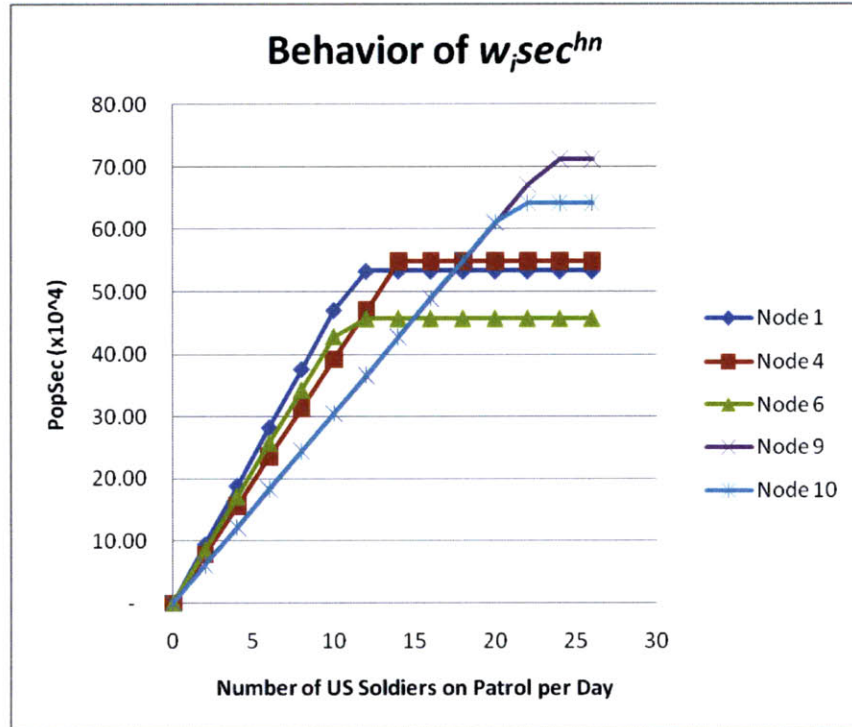


Figure 4-15: w_{sec}^{hn} Functions for Selected Nodes

Figure 4-15 shows where individual nodes dominant over the range of patrol hours. Unlike sec^v , once a node prevails in sec^{hn} , it will dominate until it reaches maximum. Node 1's combination of large population and the lowest initial effectiveness has the greatest improvement on PopSec per soldier. Node 4 overtakes node 1 if there are 14 US soldiers available. Node 4 is then surpassed at 18 US soldiers by node 9. Although node 9 and node 10 appear to be equal, the numerical data shows that node 10 is slightly above node 9.

4.4.4.3 Security (Insurgent Activity)

The emplacing a different COP configurations create multiple linear sec^{insurg} functions for each node. Independent of one another, each of the three variables: x , $pHours$, and hhc , can improve sec^{insurg} by one quarter of the maximum.

The introduction of patrolling at a node is very similar to sec^{hn} . For sec^{insurg} , the nodes are improved by additional patrol hours. The rate of improvement and maximum improvement depend on the initial insurgent activity and population. A graph similar to sec^{hn} would show where patrol hours are best allocated and which nodes dominate.

For reducing insurgent activity, the emplacement of a COP is just as important as patrolling. A combination of 50 soldiers (either combat or company headquarters) is required to increase

sec^{insurg} by one quarter. The maximum improvement depends on the initial insurgent activity, but the rate of improvement is constant. For nodes with low initial insurgent activity and high nodal weights, the algorithm will commit 50 soldiers to gain the most population security improvement.

The most straightforward decision is where to locate the headquarters and headquarters company (HHC). As stated before, there is only one HHC per battalion, so only one node in the area of operation will benefit. Once again, determining the most valuable node depends on initial insurgent activity and nodal weight. It is important to remember that only a node with a COP can base the HHC (the COP has to have minimal number of combat soldiers).

4.4.4.4 Combining the Security Functions

The combination of the three security elements into one weighted function complicates predictability. Although the objective is a combination of 3 linear functions, some of the solutions are non-intuitive. We are confident that the algorithm is performing correctly, but in many instances, a solution cannot be explained without accounting for multiple factors such as:

- Accounting for the security weights, c_j . The security weights alter which element of population security produces the most improvement.
- Accounting for node weights, w_j . Altering node weights negate all the intuition we have on the nodes based on population. A node with a small population could produce great improvements in population security because it is weighted more.
- Incorporating guard requirements. Because not all nodes are equal, a COP may be cost prohibitive if the guard force requirement is too high. This could impact efficiency in patrolling and will be examined in the experiments.
- Different unit of measure to improve population security. sec^{hm} is different from the sec^{viol} and sec^{insurg} , number of soldiers on patrol versus patrol hours per day, respectively.

In both baseline scenarios, there are cases where a COP is established at one node but the combat soldiers patrol at another. In those instances, the location of the COP reduces a higher level of insurgent activity, but it is more productive to travel to another node to patrol (sacrificing travel times) to reduce violence or improve host nation force effectiveness.

4.5 Experiments

The experiments examine some of the operational assumptions and conduct sensitivity analysis on particular parameters or constraints. Additionally, we want to test the computational limits of the model.

We segregate our experiments into five areas:

- Commander’s inputs – changing the commander’s level of risk and security weights
- Force levels – changing the number of soldiers in the unit, the unit composition, and the civilian to counterinsurgent ratio
- COP restrictions – limiting the number of COPs that can be established
- Soldier restrictions – limiting the number of soldiers per COP or on patrol in an individual node
- Computational capacity – examining a large area of operation by the algorithm

4.5.1 Commander’s Inputs

We analyze changes to the commander’s risk level and weights on the security functions.

4.5.1.1 Commander’s Level of Risk

The commander’s level of risk, p , directly impacts the guard requirements for each COP. The risk level for the baseline scenarios was set at “high,” which meant fewer guards and more available patrol hours. We hypothesized that a reduced risk level would decrease the number of COPs. Additional guards at each COP will reduce the number of patrol hours available. To maintain a relative number of patrol hours, fewer COPs will open. We also expect to see more soldiers patrolling in nodes remote to the outpost. In general, the “cost” of additional travel time in the Krasnovia scenario is often less than the cost of a moderate or large guard force in an additional COP.

The information of which nodes receive COPs and which receive patrols are shown in Tables 4-10 and 4-11, respectively, for the three levels of risk: low, medium, and high. High risk, the baseline level, requires only 90 soldiers for force protection for 9 COPs. When the scenario changes to a medium level of risk, the results show only a few deviations. For example, the number of COPs decrease by one (to 8), but the number of nodes receiving patrols remains the same at 12. The average number of combat soldiers on force protection per COP doubles from 10 to 20 soldiers. The overall increase in guard requirements cause node 26, Zephyr, to no longer be a priority for patrolling. Subsequently, Zephyr did not receive a COP either. Interestingly, while the total number of patrol hours decrease from 3171.15 to 2788.02, a 12% decrease, the overall PopSec score is 0.57590, 96% of the high risk’s improvement. We will address this result in the following section.

Node	Name	High Risk				Medium Risk				Low Risk			
		US Combat Soldiers	Force Protection	Support Soldiers	Total Soldiers	Combat Soldiers	FP	Support Soldiers	Total Soldiers	Combat Soldiers	FP	Support Soldiers	Total Soldiers
4	Dodge	141	15	0	141	245	27	0	245	299	48	15	314
7	GM	35	12	15	50	35	24	15	50	41	39	15	56
9	Infinity	35	9	15	50	35	18	15	50	35	30	15	50
10	Jeep	50	12	120	170	50	24	120	170	50	39	120	170
11	Kia	50	9	0	50	50	18	0	50	50	30	0	50
12	Lincoln	44	6	0	44	35	18	15	50	35	30	15	50
14	Nova	35	9	15	50	35	12	15	50	No COP			
21	Uplander	35	6	15	50	No COP				No COP			
22	Volvo	No COP				25	18	0	25	No COP			
26	Zephyr	85	12	0	85	No COP				No COP			
Total			90				159				216		

Table 4-10: Commander's Risk – Nodes with COPs

Node	Name	High Risk		Medium Risk		Low Risk	
		Soldiers on patrol per day	phours	Soldiers on patrol per day	phours	Soldiers on patrol per day	phours
1	Audi	3	11.28	3	11.28	2	12.58
2	Buick	9	26.11	8	29.79	8	39.79
4	Dodge	278	2036.53	270	2109.37	217	1741.70
5	Edsel	9	65.71	9	74.71	9	85.21
6	Ford	9	58.35	9	58.85	8	66.74
13	Mercury	2	14.38	2	14.38	2	12.05
15	Opel	4	31.52	4	32.85	4	32.35
16	Pontiac	10	105.81	11	114.00	10	94.47
18	Rover	8	81.52	8	81.52	8	80.52
22	Volvo	7	61.19	7	114.86	7	62.36
25	Yugo	8	68.51	8	60.17	8	67.17
26	Zephyr	73	610.24	12	86.24	11	80.47
Total		420	3171.15	351	2788.02	294	2375.41
PopSec Score		0.57783		0.5759		0.57319	

Table 4-11: Commander's Risk – Nodes with Patrols

The Krasnovia scenario at a low risk level recommends only 6 COPs. 216 out of 510 (42%) combat soldiers are required for guard duty at an average of 36 soldiers per COP. A majority of the patrolling soldiers (251 out of 294) are based in node 4, and 217 patrol in node 4. The PopSec score is 0.57319, which is 91% of the high risk. Even with such a large proportion of combat soldiers on guard, the population security improvement is comparable with high and medium risk. This shows the significant impact of a few select nodes. At all three levels of risk, the operations at node 4 account for a majority of the overall increase in PopSec score. This experiment illustrates the impact that a single node has on improving population security. The

algorithm allocates resources to dominant nodes, as discussed in the analysis on the weighted security functions.

4.5.1.2 Commanders Security Weights, c_j

The commander specifies the weights on the three security functions, where values are based on his understanding of how the population feels secure and how he will accomplish his mission. Recall that $c_1 + c_2 + c_3 = 1$.

We execute the model at all combination of c_j 's at increments of 0.05. Figure 4-16 shows the PopSec score for the discrete combinations of c_j 's. The z-axis (a third dimension coming straight out of the page) is c_3 : Host Nation Force Effectiveness.

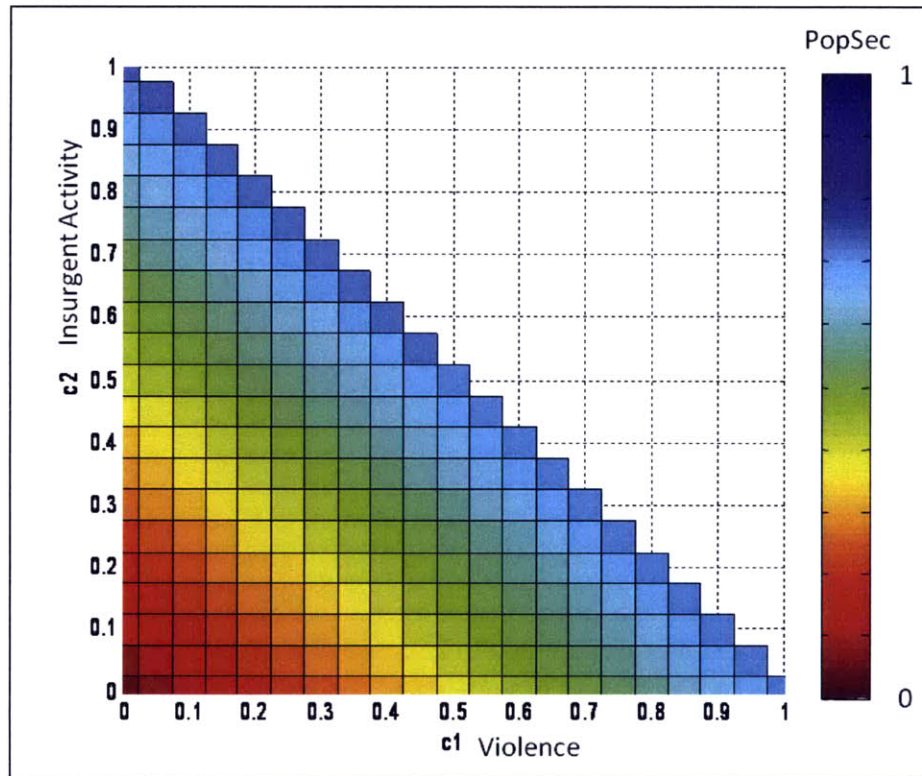


Figure 4-16: PopSec Score for Changing Security Weights

From the figure, any combination of $c_1 + c_2 = 1$, provides the same potential population security (shown along the diagonal). The Krasnovia scenario has equal potential for improving overall population security by reducing violence or reducing insurgent activity. The low PopSec score at $c_3 = 1$ is due to the extremely low initial host nation force effectiveness and because a small host nation force can only experience minor effectiveness improvement. A combination of c_j 's with a lower value of c_3 has the potential for greater improvement of PopSec score.

The results from this experiment can be used to manage expectations of commanders about their own area of operations and for higher commands. If a commander believes the local people primarily judge security by the effectiveness of host nation forces, he can expect only slight improvements in his area. However, a greater combination of weights for insurgent activities and violence will allow greater opportunities for improvement in population security.

This scenario involved a small number of host nation forces. For a scenario with many host nation forces, the improvement in their effectiveness could potentially impact population security as much as the other two elements. Additionally, a different area of operations with very high initial violence and low initial insurgent activity, or vice versa, would not show the same uniform pattern between c_1 and c_2 , but would shade darker blue toward the element with the high initial value.

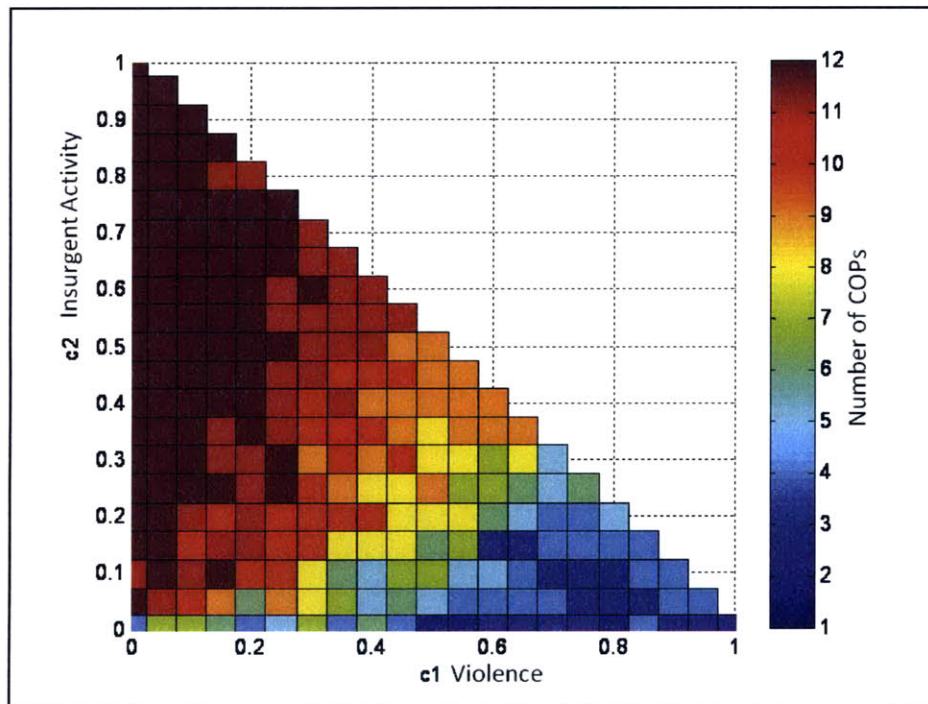


Figure 4-17: Number of COPs for Changing Security Weights

Figure 4-17 shows the number of COPs at each c_j combination when PopSec is maximized. When the value for c_1 is high, or violence reduction matters greatly, very few COPs are recommended. In these instances, all soldiers will patrol only a few extremely violent nodes that require significant patrol hours. Soldiers are based and patrol at the same node to maximize the ground time.

When $c_2 = 1$, reducing insurgent activity is most important. One third of reducing insurgent activity depends on the size of the COP. A COP with 50 soldiers (combat soldiers or company headquarters) has the greatest reduction of insurgent activity. The emplacement of 12 COPs coincides with the number of nodes with 50 soldiers.

$$\frac{570 \text{ soldiers}}{50} = [11.4] \quad (4-1)$$

COPs are established at the nodes with high levels of initial insurgent activities. Figure 4-17 shows that all combinations of c_j in vicinity $c_2 = 1$ also include 12 COPs for the reasoning above. When reduction in violence becomes moderately important, then patrol hours become more valuable, and fewer COPs are recommended.

For high weight on host nation force effectiveness, c_3 , the number of COPs recommended is only 5. When $c_3 = 1$, the number or location of COPs actually has little impact. The total number of host nation forces in this scenario is 264. Using the 3:1 ratio of host nation force to US soldier, approximately 88 US soldiers on patrol bring them to their maximum effectiveness. Because it takes very few soldiers to maximize the population security due to effectiveness, there are ample resources to decrease insurgent activities or reduce violence once those take on increased weights. Figure 4-17 shows that moving from the origin along the y-axis ($c_2 = 0.05$, $c_3 = 0.95$) the number of COPs suddenly jumps to 12, as explained above.

On a few occasions, the pattern of COPs appears inconsistent. For instance, around $c_2 = 0.8$, the two light red squares are surrounded by a number of dark red squares. This odd deviation is due to the stopping criteria for the MILP, discussed in section 3.7.2. A sufficient solution is found for each combination to stop the solver within the gap tolerance. A smaller stopping criterion would remove these irregularities, but unfortunately, not all c_j combinations converge at a lower stopping criterion.

4.5.2 US Force Levels

The Krasnovia and Cortina baseline employ a full infantry battalion. We want to investigate the impact to population security by altering unit size, unit composition, and changing the civilian to counterinsurgent ratio.

4.5.2.1 Combined Arms Battalion in Krasnovia

The combined arms battalion (CAB) has 60 fewer combat soldiers compared to the infantry battalion. With the reduction of soldiers, we would expect fewer COPs established and a reduction in the number of nodes patrolled.

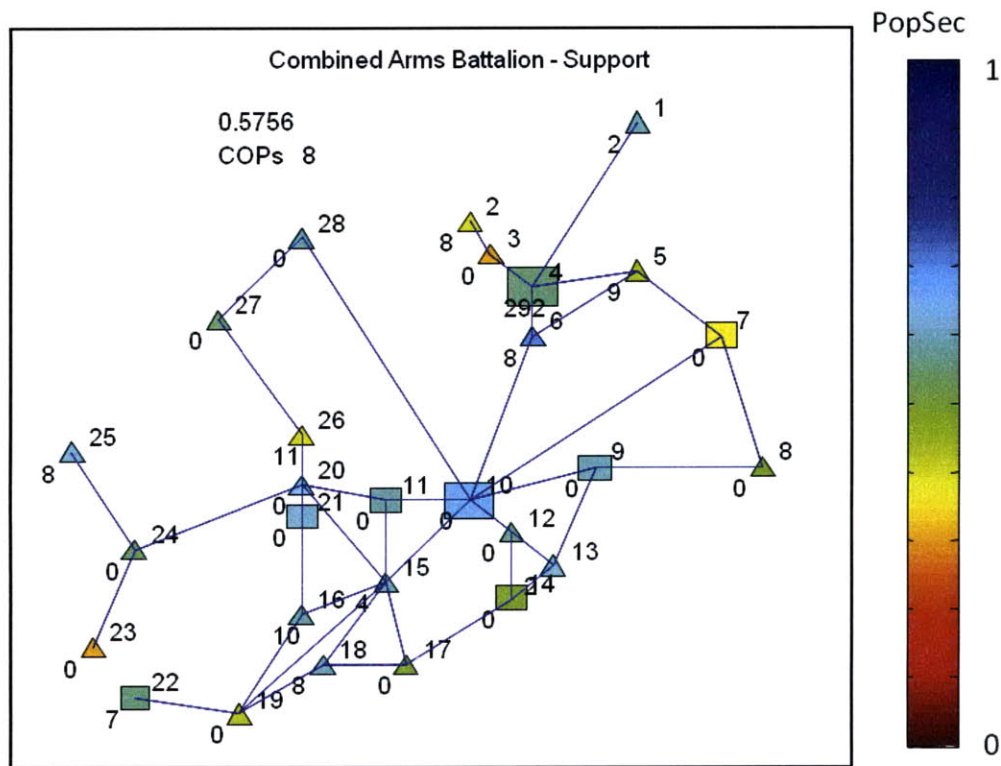


Figure 4-18: Combined Arms Battalion in Krasnovia

Figure 4-18 shows the Configuration map for the CAB. The solution recommends 8 COPs and the same 12 nodes to receive patrols as the baseline. Table 4-12 shows that the major difference from the baseline run is the number of soldiers patrolling in Zephyr. For the overall reduced number of soldiers in the unit, allocating small numbers of soldiers has a larger improvement in PopSec score compared to a large soldier appropriation to Zephyr.

Node	Name	Soldiers on patrol: CAB	Soldiers on patrol: Infantry Battalion
1	Audi	2	3
2	Buick	8	9
4	Dodge	292	278
5	Edsel	9	9
6	Ford	8	9
13	Mercury	2	2
15	Opel	4	4
16	Pontiac	10	10
18	Rover	8	8
22	Volvo	7	7
25	Yugo	8	8
26	Zephyr	11	73
PopSec Score		0.57560	0.5778321

Table 4-12: Patrolling Combined Arms Battalion vs. Infantry Battalion

The reduction by 60 soldiers is too small of a change to show noteworthy results, so we explore unit size across a large spectrum of values. Using the 50:1 ratio, the doctrinal guideline for securing Krasnovia's population requires approximately 5,700 soldiers. In a follow-up experiment, we keep the size of support troops constant but varying the overall unit size incrementally by 50 from 400 to 6000.

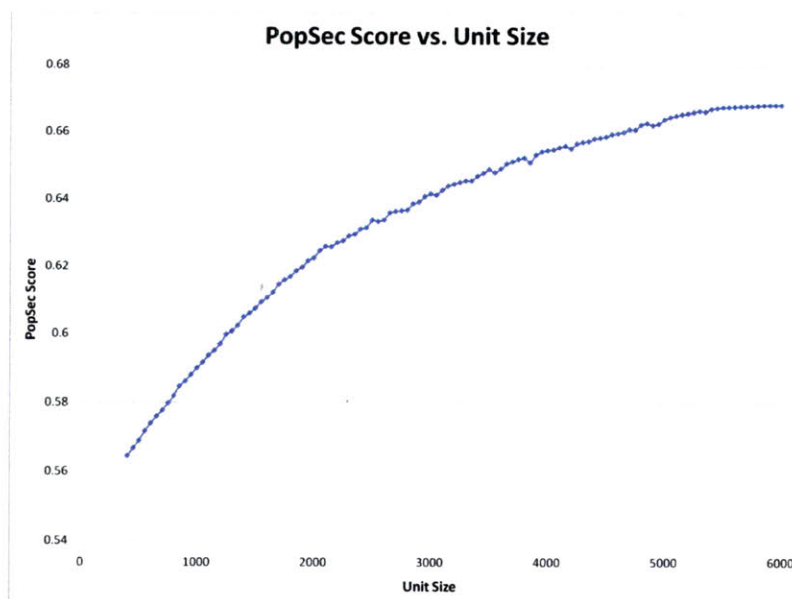


Figure 4-19: Population Security Score vs. Unit Size

Figure 4-19 shows the concave relationship between the size of the unit and the PopSec score. The increase in the size of a unit has initially greater impact on population security but eventually it begins to diminish. Ultimately, the maximum improvement is reached around 0.668 and the area shows no additional improvement. At that point, we reach the maximum of all of our population security functions for all nodes.

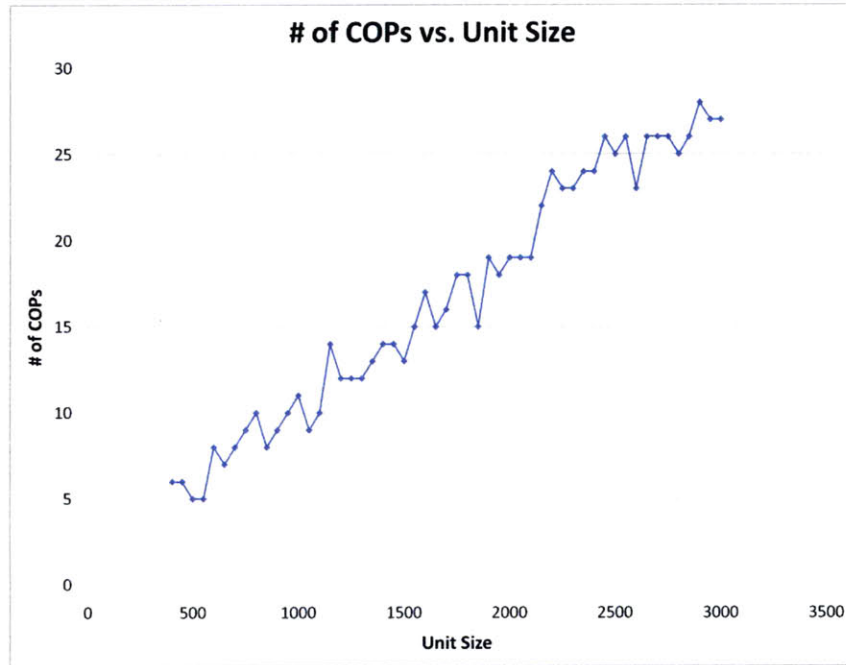


Figure 4-20: Number of COPs vs. Unit Size

Figure 4-20 shows the number of COPs has a general linear relationship to unit size but shows variance at certain ranges. A linear trend is reasonable because the “cost” (in guards) to add another COP is off-set by the addition of soldiers to the unit. As the unit size increases, the ability to add COPs increases without the loss of patrol hours.

4.5.2.2 Infantry Battalion without Support Soldiers in Krasnovia

As mentioned earlier, the commander may have priorities other than population security for the emplacement of his headquarters units. Instead of including support soldiers as decisions in the model, he may choose headquarter locations after the COP lay-down to enhance command and control. We examine the infantry battalion without support soldiers (HHC and company headquarters).

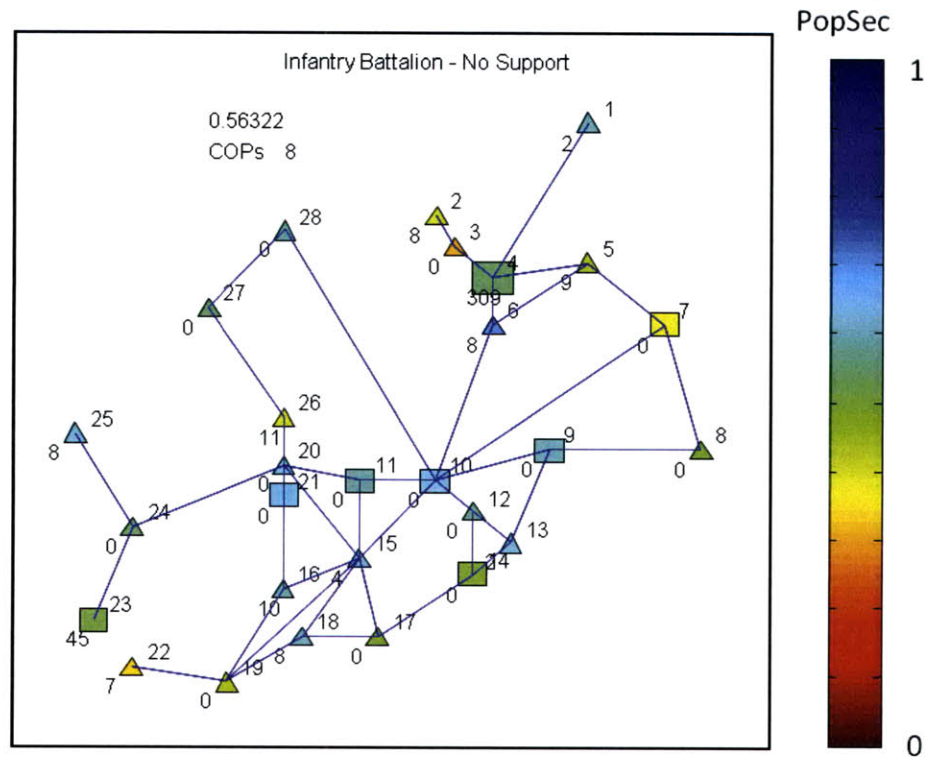


Figure 4-21: Infantry Battalion without Support Soldiers

The removal of the support elements would of course decrease the PopSec score; however, we are more interested in changes to the Configuration. Figure 4-21 shows the recommended 8 COPs, versus 9 for the baseline. Table 4-13 gives the exact figures on COPs compared to the baseline. The total strength at each COP varied slightly. The algorithm replaced the company headquarter soldiers with combat soldiers to maintain the 50 soldiers required to maximize reduction in insurgent activities. The increases in combat soldiers in those four COPs accounts for the removal of 1 COP. The patrolling schema is very similar; both patrol the same 12 nodes with very similar patrol sizes. The results show that if a commander wishes to emplace his headquarters after executing the model, the nodes selected for COPs will be very similar.

Node	Name	Without Support				With Support			
		Combat Soldiers	Force Protection	Support Soldiers	Total Soldiers	US Combat Soldiers	Force Protection	Support Soldiers	Total Soldiers
4	Dodge	159	15	0	159	141	15	0	141
7	GM	49	12	0	49	35	12	15	50
9	Infinity	50	9	0	50	35	9	15	50
10	Jeep	50	12	0	50	50	12	120	170
12	Lincoln	No COP				44	6	0	44
11	Kia	50	9	0	50	50	9	0	50
14	Nova	50	9	0	50	35	9	15	50
21	Uplander	50	6	0	50	35	6	15	50
23	Wrangler	52	7	0	52	No COP			
26	Zephyr	No COP				85	12	0	85

Table 4-13: Infantry Battalion COPs with and without Support

4.5.2.3 Civilians to Counterinsurgent Ratio

The baseline scenario uses the guideline 50:1, civilians to counterinsurgent ratio, from doctrine. We wanted to explore how different values would impact our results. Recall that the ratio impacts all three elements of population security; the ratio directly determines how many US soldiers or patrols hours are required to secure a node.

We intuitively expect higher levels of security for larger ratios, as it takes fewer soldiers to secure the population. Figure 4-22 shows PopSec score versus the ratio. The increase in PopSec score is concave. From this we can see potential diminishing returns on greater ratios. Understanding this behavior is important for general planning purposes. Appreciating what can be accomplished at each ratio will allow commanders to decide unit sizes for particular areas. The green dashed line in Figure 4-22 shows the maximum improvement in PopSec score that this area of operation could achieve. The 500:1 ratio is very close to reaching that maximum.

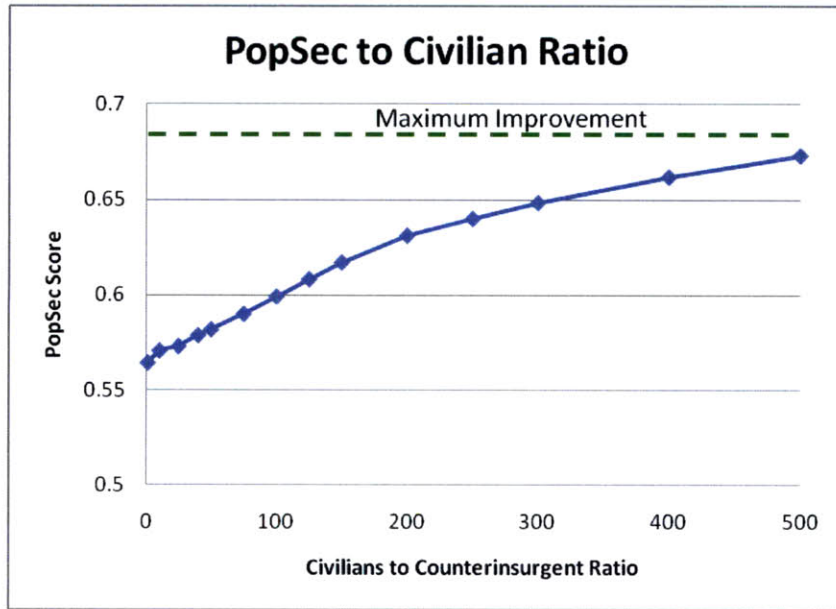


Figure 4-22: PopSec Score vs. Civilian to Counterinsurgent Ratio

4.5.3 COP Restrictions

Operationally, a unit may be restricted to a certain number of COPs. These restrictions result from security agreements with the host nation government or can be imposed by the higher level commander. For instance, the host nation government may limit the number of bases that US soldiers can occupy in a region. We examine how a prescribed number of COPs impact the population security score and the Configuration. From the fixed number of COPs, we can also analyze how an upper or lower bound would impact population security. With our infantry battalion, the maximum number of COPs is 20 (based on the minimal manning constraint: Equation 3-16). We examine the results of dictating an exact number of COPs from 1 to 20 at each of the three levels of risk.

Figure 4-23 shows the PopSec score versus the number of COPs for each level of risk.

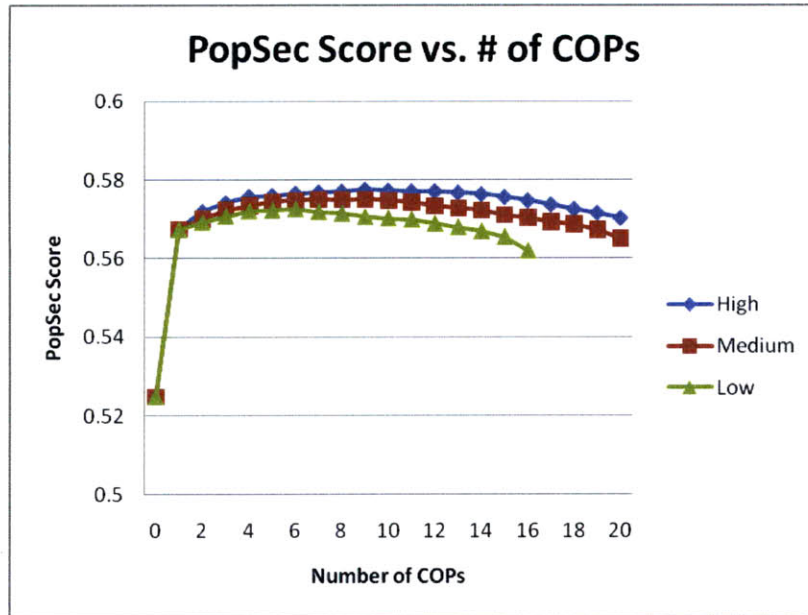


Figure 4-23: PopSec Score vs. Number of COPs – Krasnovia

The scores are fairly steady across the range of COPs for the high and medium levels of risk, but it starts to trail-off for the low level of risk. The low level of risk is adding, on average, 36 guards for each additional COP. Eventually, there are not enough unassigned soldiers remaining to meet the guard requirement after the sixteenth COP.

We can compare the PopSec scores relative to the greatest improvement for each level of risk. Figure 4-24 shows the percent of the maximum PopSec score by COP size for each level of risk.

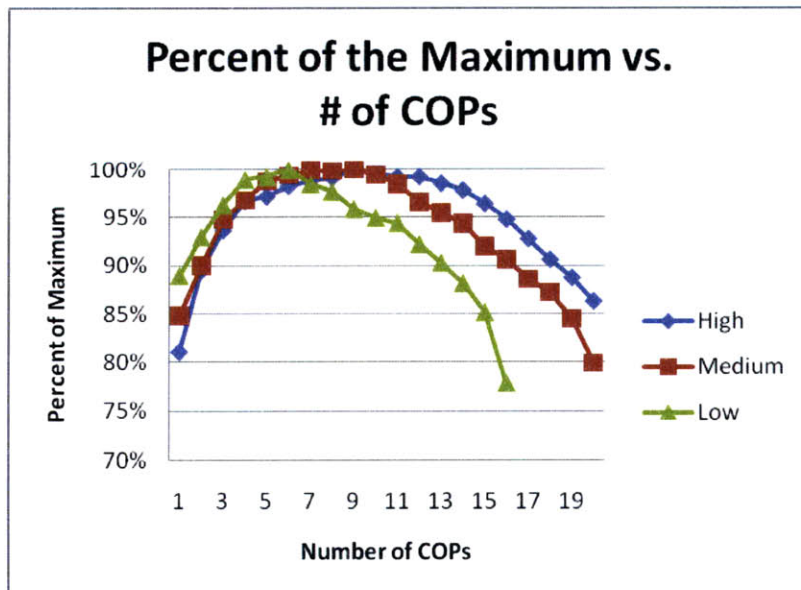


Figure 4-24: Percent of Maximum PopSec vs. Number of COPs – Krasnovia

For the high level of risk, any number of COPs ranging from 3 to 18 would be within 10% of the maximum security. That upper limit drops to 16 for medium risk and 14 for low risk. As mentioned before, the impact of a small number of nodes accounts for a majority of the population security. For the Krasnovia scenario, the establishment of more COPs requires additional force protection but the close proximities of the nodes allow the soldiers to continue to patrol in select nodes. In a situation similar to this scenario, the model shows a commander that he has great flexibility in how many COPs he emplaces to achieve similar results.

We also looked at Cortina which has longer travel time between nodes. Figure 4-25 shows a similar shape to Krasnovia.

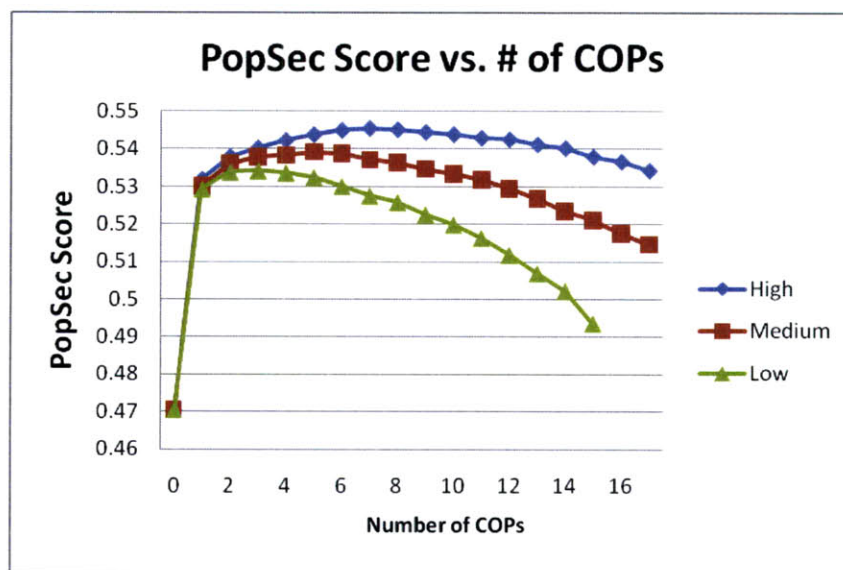


Figure 4-25: PopSec Score vs. Number of COPs – Cortina

While the high level of risk remains steady, both the medium and low fade more rapidly than for Krasnovia. Again, we examine the relative improvement of population security compared to the maximum. Figure 4-26 shows that Cortina is more sensitive to additional COPs after the optimal number of COPs is surpassed.

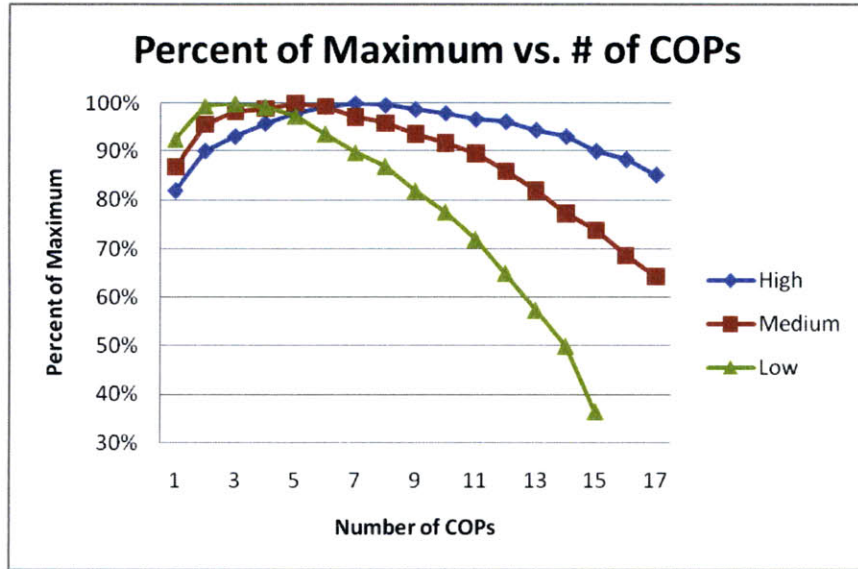


Figure 4-26: Percent of Maximum PopSec vs. Number of COPs – Cortina

For the high level of risk, the percent of maximum improvement is still very elevated through the range of COPs. The medium risk trails off above 10 COPs. The low level of risk depreciates steadily: at 9 COPs, the PopSec score is 80% of the maximum improvement. Again, the additional guards for each COP and the long travel distances are reducing available patrol hours and preventing efficient use of all soldiers.

4.5.4 Soldier Restrictions

During operations, if a commander concentrates too many resources on a limited number of nodes, a perception of favoritism or bias could fuel inter-group tensions. The commander may decide to increase coverage throughout the area of operations either by limiting the size of COPs or the size of patrols, but still concentrate on the areas that provide the most PopSec improvement.

4.5.4.1 Limit Number of Soldiers Per Combat Outpost

A commander may impose a limit on the number of soldiers allocated to a COP. A smaller COP may make a local population more tolerant to having an outpost in their neighborhood. We impose a new constraint on the problem:

$$v_i \leq 50y_i \quad \forall i \quad (4-2)$$

We choose 50 because it is roughly the size of a reinforced platoon and is the number that maximizes reducing insurgent activity. Even with this restriction, we still require one node to receive all 120 soldiers from the HHC.

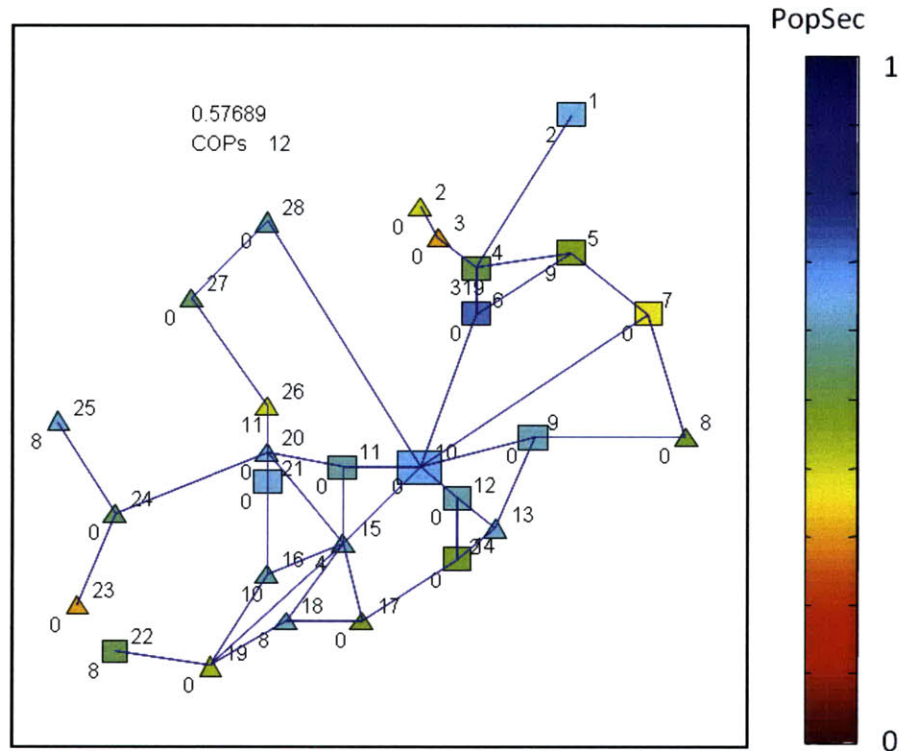


Figure 4-27: Limited Number of Soldiers Per COP

With the inclusion of the new constraint, Figure 4-27 shows an additional 3 COPs are recommended beyond the baseline, but the patrols generally remain the same. All of the nodes with host nation forces have US soldiers patrolling, and node 4 still receives a majority of the soldiers patrolling. By imposing this new constraint, the PopSec was only reduced by a small fraction. Again, we see the close proximity of the nodes in the Krasnovia scenario allows for a robust solution. The burden for guarding additional COPs does little to diminish the ability to patrol at specific nodes.

4.5.4.2 Limit Number of Soldiers on Patrol

The commander may instead not wish to concentrate patrolling too heavily on any one node. Operationally, it is probably unrealistic to send over half of the combat forces to one node every day as seen in the Krasnovia baseline. He can expand the area of patrols to disrupt insurgents in more areas. We introduce a new constraint:

$$\sum_{k=1}^K x^p_{ki} \leq 100 \quad \forall i \quad (4-3)$$

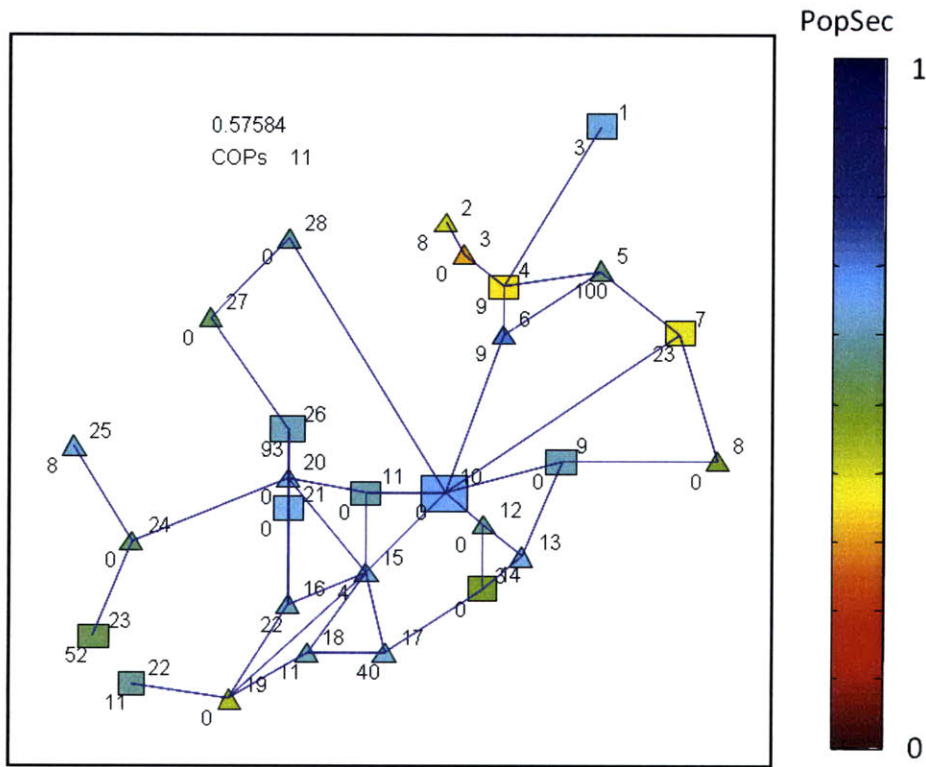


Figure 4-28: Limited Number of Soldiers on Patrol

When patrols are limited to 100 soldiers per node, the schema changes considerably. Figure 4-28 shows patrolling soldiers are now spread over 15 nodes. The 12 nodes with host nation forces still receive soldiers but now nodes 7, 17, and 23 also receive patrols. Node 4 receives only the number of soldiers required to maximize host nation force security. Node 5 receives the maximum number of patrolling soldiers (100), but does not receive a COP because it has very few insurgents; node 5 is close to nodes 4 and 7 so soldiers lose little ground time by travelling but still impact insurgent activity at their base node.

4.6 Testing the Model

With the current software configuration and using a Dell Optiplex 740 desktop with AMD Athlon 64 X2 Dual Core Processor 5600+ 2.91 Ghz and 2.00 GB of RAM, the algorithm usually solves within 20 seconds using a gap tolerance less than 0.002. Occasionally, the solver would not converge because the tolerance gap was too small. In those instances, the solver will

eventually stop due to limited memory after approximately 20 minutes. A small adjustment from 0.002 to 0.003 (or as high as 0.005) allows all experiments to converge.

To test the computational capacity of the algorithm in this software configuration, we examine a scenario with one hundred nodes. The area of operation is a ten node-by-ten node system where all adjacent nodes are 30 kilometers apart – total area is 270 kilometers by 270 kilometers. For initial conditions, we sample from the same distributions as the Krasnovia and Cortina scenarios. Additionally, we sample from a uniform distribution for the initial violence and for road category between nodes:

$$violInitial \sim U(0,1)$$

$$p_{road\ category}(k) = \begin{cases} 0.25, & \text{if } k = 1,2,3,4 \\ 0, & \text{otherwise} \end{cases}$$

This large area of operation solves at a gap tolerance of 0.004 in 345.09 seconds going through 20,650 sub problems. The larger number of nodes slows the solver down considerably. If we are willing to accept a less optimal solution, the algorithm solves in 22.36 seconds when the gap tolerance is 0.01. The PopSec score for the larger gap is 91% of the smaller. A 90% reduction in solution time only cost 9% of population security improvement. Given the short solution time, it is important to find a tolerance gap that explores as much of the solution space as possible.

Solution time depends on the number of nodes, but also the particular parameters for the scenario. If the algorithm can eliminate a number of sub problems, it solves quickly. If the characteristics of nodes are very similar, the algorithm has to explore many more sub problems to test all the combinations.

5 FUTURE RESEARCH

The accuracy and realism of the COP emplacement model developed in this thesis can be expanded and improved in a number of ways. We believe an important initial step is to validate as much of the model as possible with current operational data. Operational data will allow the creation of formulas for quantifying the initial conditions. A more realistic model also needs to include a dynamic aspect to account for insurgent and population reactions. Furthermore, we propose operational considerations to be implemented. Given the license requirements for the software used in the model, the operational use of this model is limited in the field, but could be incorporated into “reach-back” for units deployed. We also believe this model would find applicability in military war games and simulations.

5.1 Validate

Many aspects of the model currently use representative data, but actual operational data could confirm assumptions or allow for appropriate adjustments. One major step is to create formulas to quantify each initial condition on a 0-1 scale: attacks, violence, host nation force effectiveness, and insurgent activity. The current and recent data maintained by the military has much of the information to create, confirm, and test formulas that could be applied to individual nodes. Data on violence and attacks has ample detail and is well organized. The data on insurgent activity is less well organized, is not maintained centrally, and requires knowledge of which military organizations are collecting certain data. For information that is incomplete or does not exist in a database, other types of written records may suffice. Sources of information on insurgent activities include written products, such as patrol debriefs and intelligence summaries. The creation of a formula for host nation force effectiveness would require access to transition teams’ reports and records.

Unfortunately, most of the data maintained by the military is classified as secret. The best method to develop formulas with classified data is to transfer the model to a secret network. Creating the initial condition formulas should begin by delineating nodes; defined locations, such as specific parts of a city, will facilitate accuracy in data mining techniques. Additionally, data sources must also be scrutinized for useful content. Data coming directly from patrols would be more beneficial than data that is output from analysis. Finally, for other data that is not already gathered by the military, a request to units currently deployed for collection requirements could

be submitted through military channels. Depending on the nature and ease of collection, it may become part of intelligence collection requirements for deployed units.

Once formulas for calculating initial conditions are established, one should attempt to validate elements of the population security function. Although there is historical data before and after emplacement of individual COPs, it will be difficult to use historical data to precisely validate the population security functions. External factors such as social or religious events, inconsistencies in reporting due to the rotation of units, and seasonal impacts may misconstrue the effect of COP emplacement or patrolling. The impact of these external factors should be removed or offset as much as possible. At a minimum, the general shape and size of population security functions could be determined using the historical data.

Further discussions with subject matter experts, especially current or recent commanders, can help refine the population security functions and the constraints, such as minimal manning or force protection requirements. Former commanders can help us determine if the presence of a COP improves population security by reducing violence and should be included in the function.

5.2 Dynamic Considerations

In its current static form, the algorithm does not consider changes in insurgent behavior; the solution provides a steady state value after a 3-month period. Future research could enhance the model by making it dynamic. The decision to emplace a COP is a long term decision and anticipating the insurgents' reaction to COP positions could expose second and third order affects. More importantly, a dynamic element that includes the reaction of the population would make a vast improvement. Including aspects of game theory to incorporate insurgents' or population's responses could make the model a more robust tool. Realistically, US units will partially alter their operations depending on insurgents' behavior and the local population's reactions. The position of a COP will not change but the location and size of patrols may adjust. As will be mentioned below, a simulation of a dynamic model could provide valuable results for varying scenarios. The dynamic aspect will allow a commander to alter his patrol plan in response to the changing circumstances and determine if a particular COP configuration supports the patrol changes.

Incorporating dynamic considerations into the model would take considerable reformulation of the model. One would need a general understanding of the insurgents' reactions. This would

involve extensive research with subject matter experts and assistance from military agencies. The Training and Doctrine Command Intelligence Support Activity (TRISA) analyzes worldwide threats and could provide enemy responses to include in the algorithm. The population responses to a COP location or to patrolling will be even more difficult to collect and include. Given the uncertainty of both insurgent and population behaviors, these items would be modeled stochastically.

5.3 Operational Considerations

Although a number of assumptions were made to simplify the model, the one preventing additional host nation forces should be removed. Additionally, the model should include other types of battalions.

5.3.1 Adding and Repositioning of Host Nation Forces

When creating the model, we used a consistent number of host nation forces to formulate host nation force effectiveness and patrol hours. Operationally, more host nation forces are paramount to a successful counterinsurgency. Security forces are continually being recruited, trained, and introduced into established areas of operation. Adding new host nation forces can radically alter the security situation and contributes greatly to improving population security that is provided by the host nation. Including additional forces in the model requires careful analysis to determine how to assess and compare the new forces to the experienced host nation forces. The model currently treats the host nation forces at each node as a collection of equal soldiers. The introduction of new soldiers deviates from this assumption. The guidelines on how to regard the less experienced soldiers would need to be thoroughly established.

In addition, host nation units are repositioned to different areas for operational or political reasons, or to assist in a turbulent area. The repositioning of trained forces will also alter the computation for host nation force effectiveness. The model will need to account for combining host nation forces with varying levels of effectiveness.

5.3.2 Additional Battalion Types

The model was set up to accommodate a fully manned combined arms or infantry battalion. Since we do not consider equipment, expanding the model to include other types of battalions would involve minor adjustments to account for different personnel configurations, especially

the number and composition of headquarters. All types of battalions contain a headquarters and headquarters company (HHC) and two or more “line” companies. The combined arms battalion has 4 line companies (two tank companies and two mechanized infantry companies). An artillery battalion has only two line companies (called batteries), while the Stryker infantry battalion has 3 line companies. The number of support soldiers in each line company headquarters varies by company type.

Recall that during operations, additional companies can be attached to or detached from battalions. A combined arms battalion could potentially have five line companies if one more was attached or three companies if one was detached. There is no limit to how many subordinate companies a battalion can have, but usually, because of command and control issues, it is not above six.

Another consideration is that some of the line companies contain only support soldiers. The brigade special troops battalion has a military intelligence company and a network signal company, both containing only support soldiers. For these companies, the model would regard them more like an HHC than an infantry company since support soldiers do not patrol or conduct guard and only impact population security as it relates to reduction in insurgent activity.

The overall size of the unit is already an input to the model. The attachment or detachment of companies can be added or subtracted from the original battalion total. The size of the HHC and the size and number of line company headquarters could become individual inputs to account for different unit configurations. The model would also require an input to distinguish line companies with support soldiers from those with combat soldiers.

5.3.3 Assisting with Uncertainty

A commander will have uncertainty in setting weights for nodes and the security function. After operating for a few months, he may realize he has misinterpreted what the population deemed important, but he has already used valuable time and resources to establish COPs. By modifying the model to be used in reverse, it could provide a range, or confidence level, for the commander’s weights prior to execution. By altering to receive the Configuration as an input, the model could output the range of commander’s weights appropriate for specific Configuration. That way, the commander and staff can analyze likelihood of success for different Configurations based on certainty of commander’s weights.

This idea could be extended to provide ranges in other input parameters that are uncertain such as initial conditions at the nodes. The determination of initial violence, insurgent activity, and host nation force effectiveness will be based on limited data. Using the model in reverse to see the applicable ranges for a specific Configuration will provide greater insight and confidence.

5.4 Operational Usage

Most deployed military units use Microsoft software exclusively. The ability for forward deployed units to execute the COP emplacement model is challenging. However, the Army has been using a reach-back capability that allows deployed commanders and staffs to request assistance on challenging problems from analysts in the US. Training a few of these analysts would allow almost all deployed units the ability to utilize this model as a tool. Designing an Excel file to receive the inputs could ensure a simple and accurate report. The forward deployed staff could easily input parameters into a preformatted worksheet and return it with minimal training. Within the model, a few software code adjustments could read the Excel spreadsheet directly.

Additionally, the model could be incorporated into war games to evaluate doctrine and decision making. The military conducts numerous war games, many using simulators, to test and evaluate changes to doctrine. Either in its current form or with dynamic aspects included, simulating the model can show where potential difficulties exist for COP placement or patrolling courses of action. The COP model could add another element of realism to whatever concept is being tested in the war game.

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6 CONCLUSION

At the beginning of this research, we introduce the fundamentals of insurgency and how they relate to security. Lacking a succinct formulation of population security from military doctrine, we present a rational way to address it in a mathematical model. The model includes three important facets of population security: reducing violence, reducing insurgent activities, and improving host nation force effectiveness. We create functions that compute improvements to each facet of population security through emplacing combat outpost (COPs) and patrolling. The commander's inputs, such as node and security weights, reflect his understanding of the situation, his mission, and the local people. The commander also sets his level of risk as it pertains to force protection in COPs.

The model considers an array of operational inputs in a battalion area of operation that is represented as a graphical network. We use piecewise linear approximation to allow the problem to be solved by a mixed-integer linear program (MILP). Based on trade-offs in patrolling and self-protection, the algorithm determines the locations and sizes of COPs and patrols. The computational time to execute the MILP is on average, less than 30 seconds for a moderate size battalion area of operation. Some solutions are non-intuitive, and in those instances, a solution cannot be explained without accounting for and understanding multiple factors.

The results lead to a number of conclusions about COP placement. The commander's node weight and security weight have a tremendous impact on how COPs are distributed. When the security weight on reducing violence is high, very few COPs are recommended. A small number of COPs allows more soldiers to patrol at the violent locations. Numerous COPs are recommended when the security weight for reducing insurgent activity is high. Many COPs mean insurgent activities are disrupted at more nodes. The results show a small host nation force does not affect COP locations but draws a small US patrols to impact improvements in effectiveness.

As intuition might suggest, for a small area of operation, the emplacement of COPs is not that critical for population security because patrols can easily access most locations. With a large and more desolate area of operation, the placement of COPs becomes increasingly more important and challenging. The results show that the best way to improve security for the current formulation is to mass resources on a particularly unsecure node. However, most commanders would be uncomfortable with such a large commitment to one area. An adjustment to the

population security function or additional constraints would prevent the large patrols to a single node. We expect most commanders would want to impose constraints on COP size and patrol size to prevent too many resources going to one node.

We recommend some improvements of the model to make it a useful tool for commanders understand their areas of operation. Several aspects of the model require validation using operational data. Extending the model to include a dynamic aspect would allow for insurgent and population reactions to our COP locations and patrols.

APPENDIX A: ABBREVIATION AND ACRONYMS

Abbreviation/ Acronym	Term
AO	area of operation
BCT	brigade combat team
CAB	combined arms battalion
CO	company
COP	combat outpost
FM	field manual
FOB	forward operating base
HBCT	heavy brigade combat team
HHC	headquarters and headquarters company
HMMWV	high mobility, multi-wheeled vehicle
HQ	headquarters
IBCT	infantry brigade combat team
JP	joint publication
JSS	joint security station
MILP	mixed-integer, linear problem
MRAP	mine resistant, ambush protected
SBCT	Stryker brigade combat team
TRISA	Training and Doctrine Command Intelligence Support Activity
US	United States

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APPENDIX B: MASTER TABLE OF VARIABLES AND PARAMETERS

Symbol	Name	Unit	Type	Min	Max
PopSec _i	Population security at node i	-	Obj funct	0	1
sec ^v _i	Security by reducing violence at node i	-	-	0	1
sec ^{insurg} _i	Security by reducing insurgent activities at node i	-	-	0	1
sec ^{hn} _i	Security from confidence in host nation forces at node i	-	-	0	1
x ^f _i	Number of combat soldiers assigned force protection duties at node i	combat soldiers	Integer Decision Variable	0	n
x ^p _{ik}	Number of combat soldiers based in a COP at node i that patrol in node k	combat soldiers	Integer Decision Variable	0	n
y _i	1 for a COP; 0 without a COP	-	Binary Decision Variable	0	1
hhc _i	Number of headquarters and headquarters company soldiers based at node i	support soldiers	Binary Decision Variable	0	120
cohq _i	Number of company headquarters' soldiers based at node i	support soldiers	Binary Decision Variable	0	15
x _i	Number of combat soldiers (patrolling and force protection) based at node i	combat soldiers	Integer Dependent Variable	0	n
supp _i	Number of support soldiers from HHC and company headquarters based at node i	support soldiers	Integer Dependent Variable	0	n
v _i	Number of all soldiers (combat and support) based at node i	soldiers	Integer Dependent Variable	0	n
phours _i	Number of patrol hours per day for node i	hours	Dependent Variable	0	-
copVuln _i	Vulnerability of COP at node i	-	Integer Dependent Variable	5	15
forpro _i	Number of combat soldiers required for force protection	combat soldiers	Integer Dependent Variable	6	54

Symbol	Name	Unit	Type	Min	Max	Initial Value
w_i	Commander's rating of node i	-	parameter	0	1	each node proportional to population
c_j	Commander's rating of element of security j	-	parameter	0	1	$c_1 = 0.5$ $c_2 = 0.3$ $c_3 = 0.2$
p	Commander's level of risk	-	parameter	Low	High	High
n	Number of soldiers in the unit	soldiers	parameter	0	∞	690
m	Minimum number of US combat soldiers stationed at a COP	combat soldiers	parameter	0	n	25
dutyday	Duty day of the average soldier	hours	parameter	0	24	8
ccRatio	Civilian to counterinsurgent ratio	-	parameter	0	∞	50
nodePop _i	Civilian population in node i	people	parameter	0	∞	
hn ^p _i	Number of host nation forces patrolling in node i	host nation forces	parameter	0	∞	
violInit _i	Initial level of violence at node i	-	parameter	0	1	
effInit _i	Initial effectiveness of host nation forces based at node i	-	parameter	0	1	
insurgActInit _i	Initial level of insurgent activity at node i	-	parameter	0	1	
effect _i	Effectiveness of host nation security forces at node i	-	parameter	0	1	
effdelta _i	Change of effectiveness of host nation security forces at node i	-	parameter	0	1	
attack _i	Initial level of attacks in node i	-	parameter	0	1	
copQual _i	Quality of COP location at node i	-	parameter	Low	High	
d_{ik}	Distance from node i to neighbor node k	km	parameter	0	∞	
u_{ik}	Speed between nodes i and k based on road conditions	km/h	parameter	0	45	
α_{ik}	Arc travel time between neighboring nodes i and k	hours	parameter	0	∞	
τ_{ik}	Travel time from node i to node k	hours	parameter	0	∞	
ξ_{ik}	Ground time at node k for soldiers based at node i	hours	parameter	0	dutyDay	

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